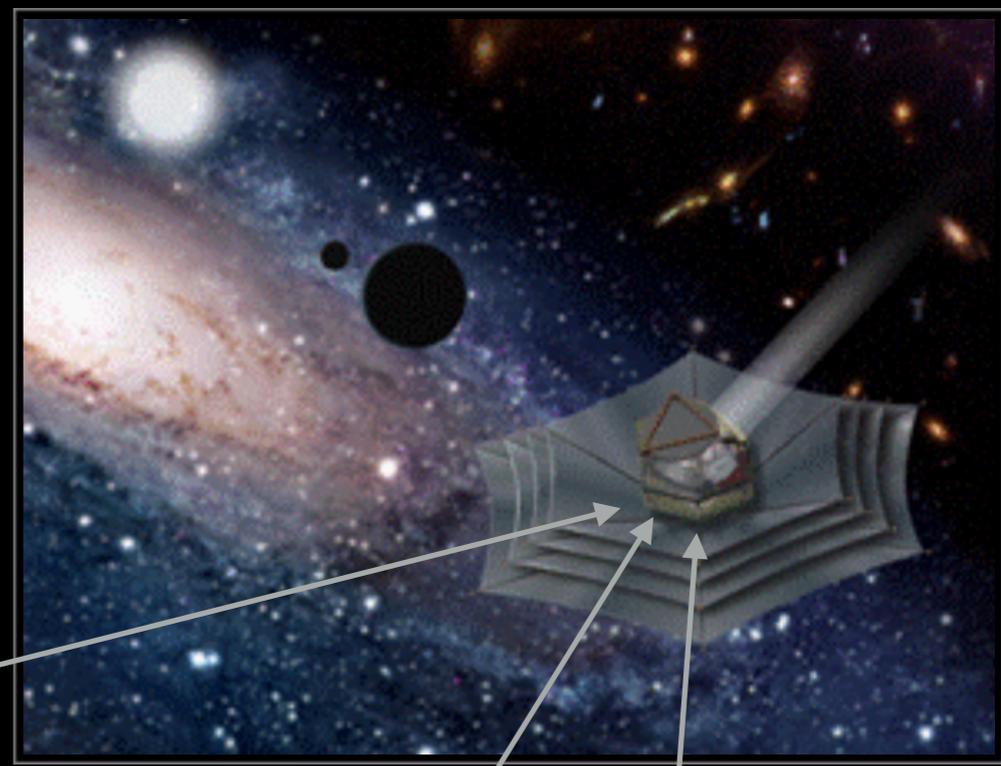
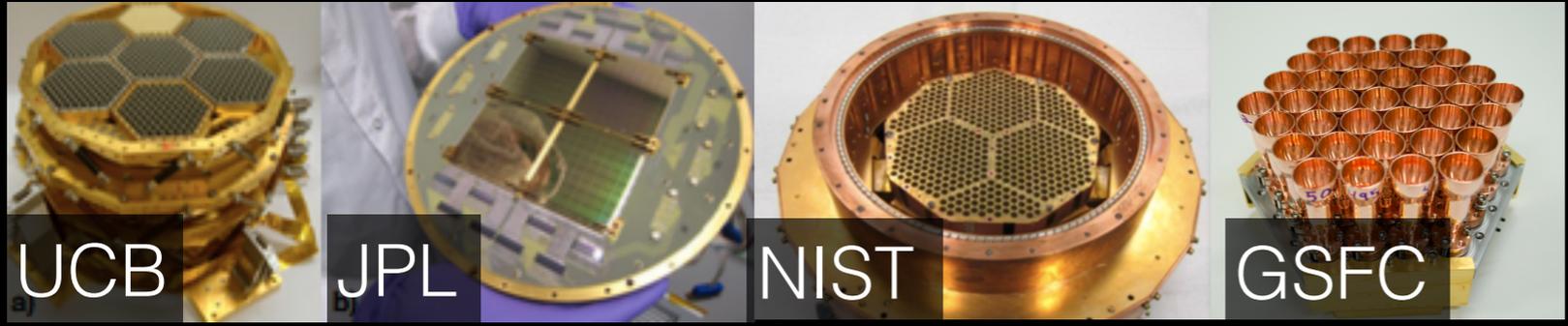


Technology Landscape for the Inflation Probe

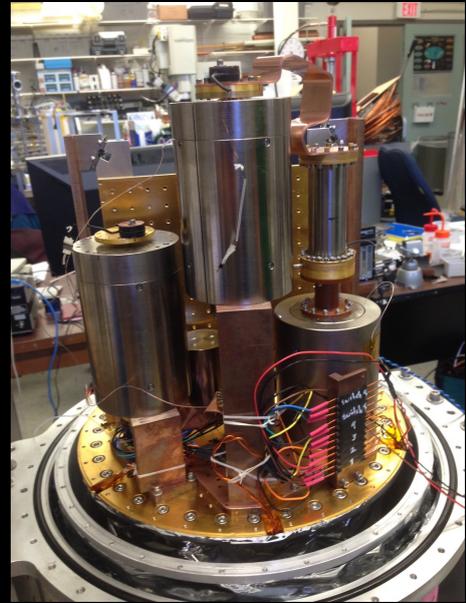
Jeff McMahon 



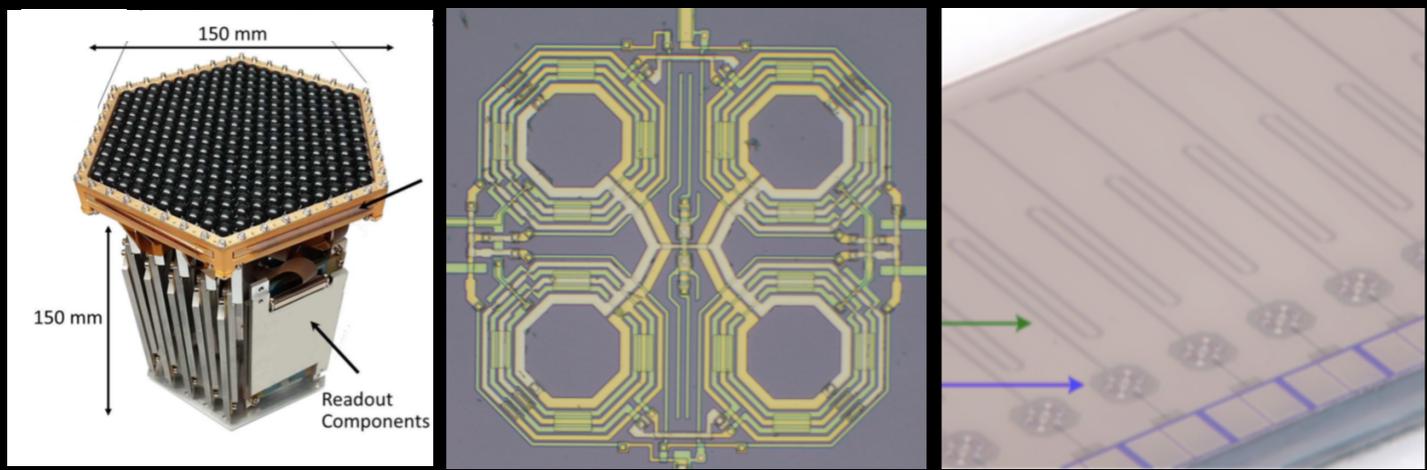
detectors



cryogenics



& readout



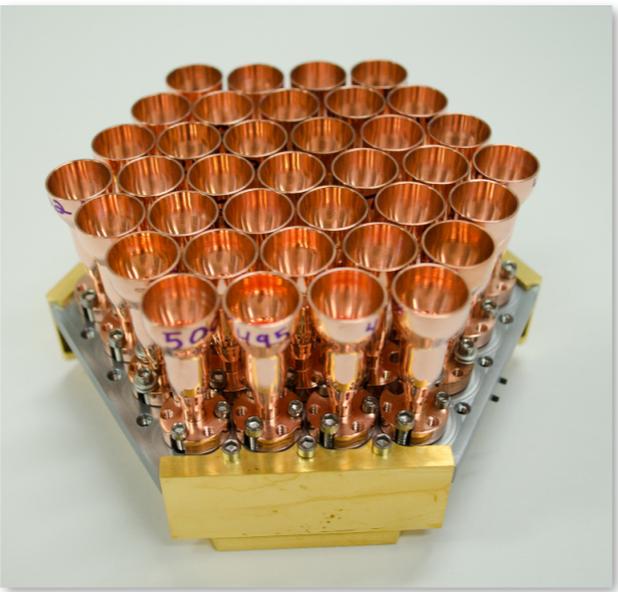
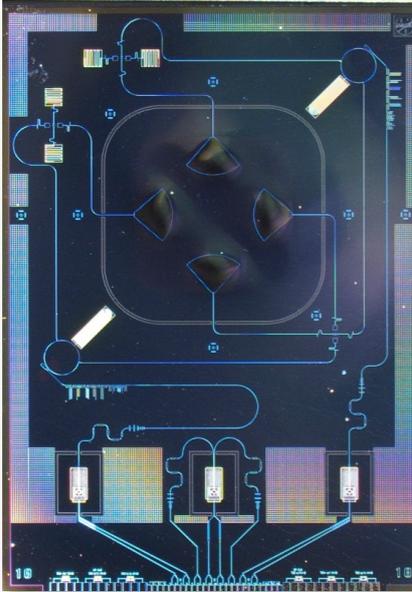
optics



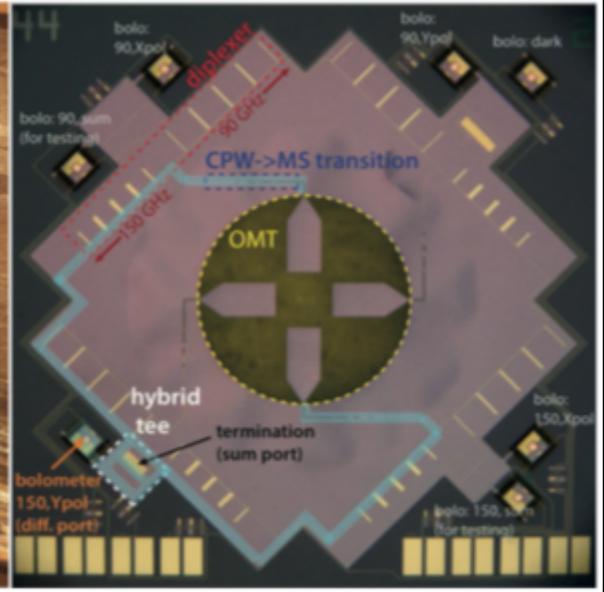
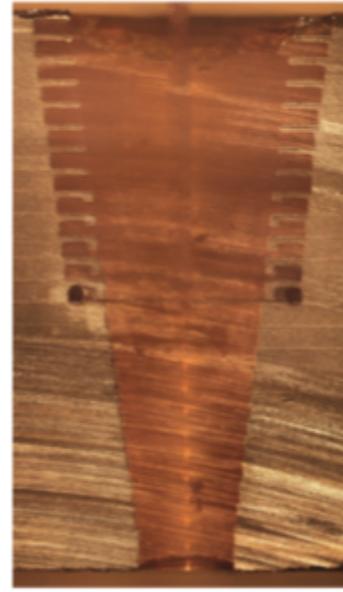
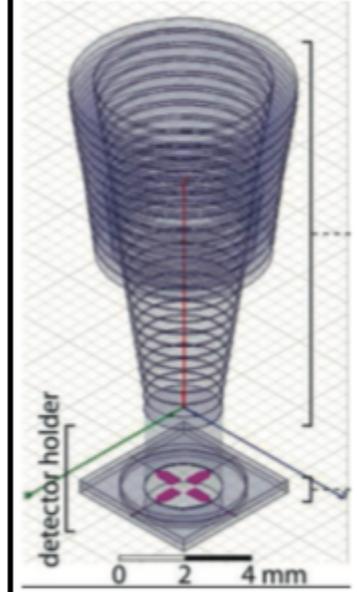
Detector Arrays

Horn Coupled

GSFC

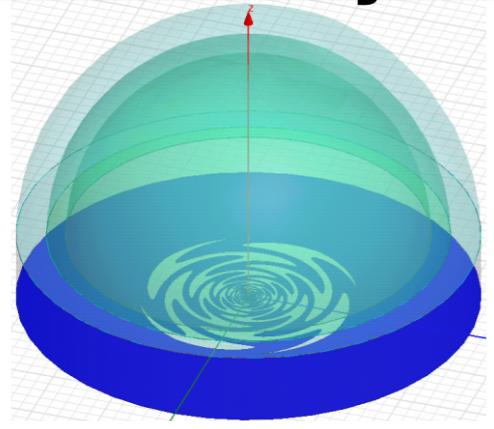


NIST+

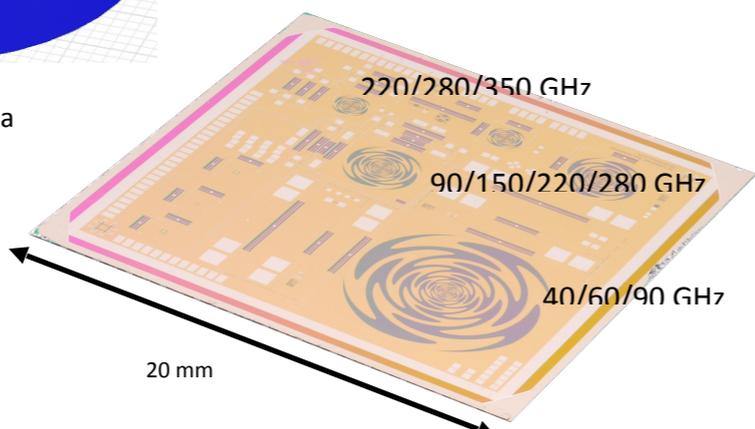


Planar Antennas

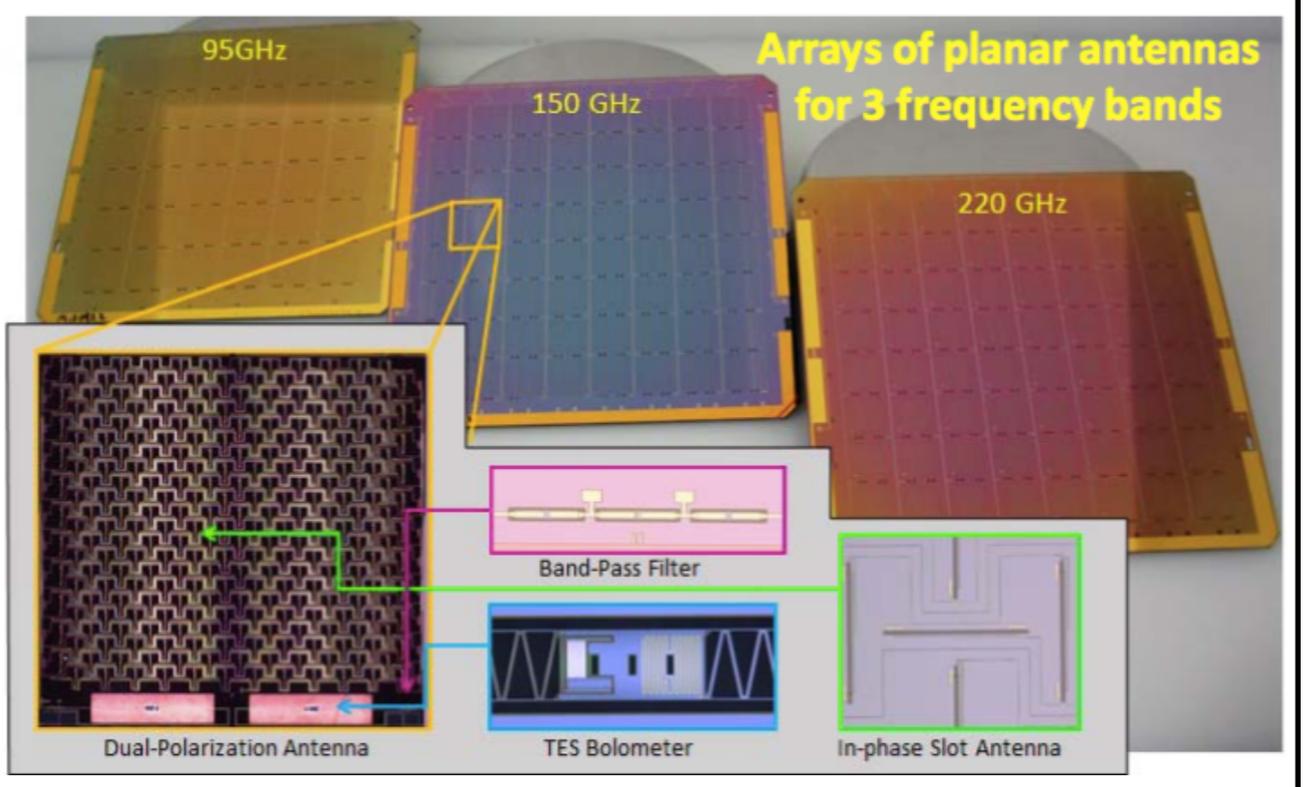
Berkeley

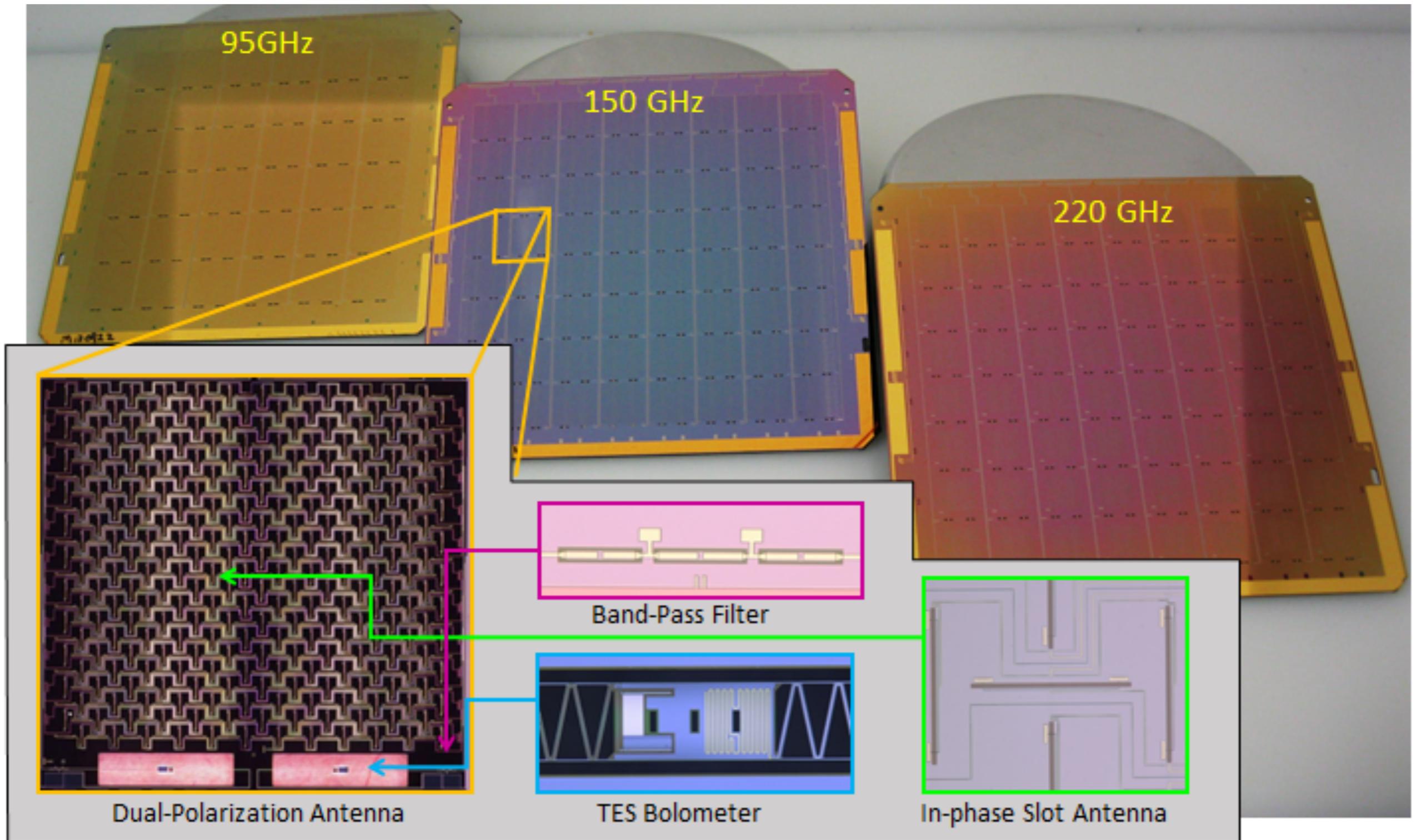


Lenslet Coupled Antenna



JPL

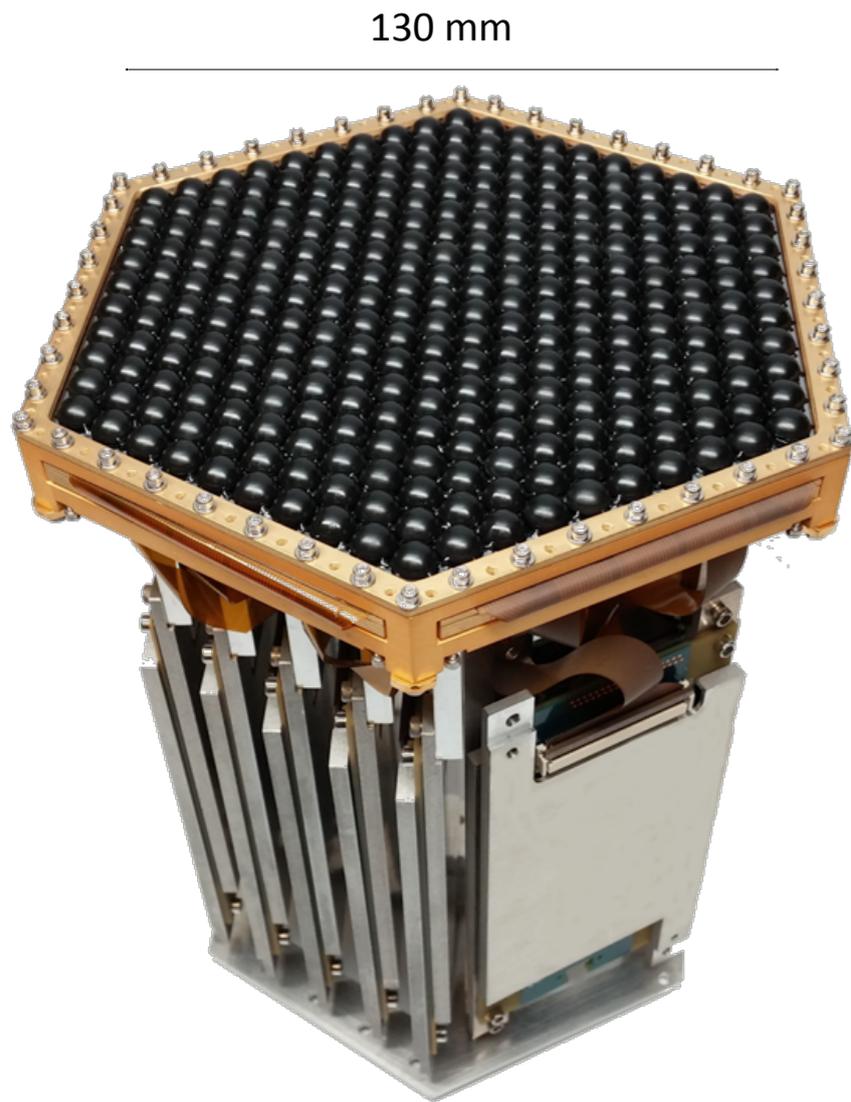




Science Applications:	BICEP/Keck (95/150/220)
88 tiles in scientific use	BICEP3 (95 GHz)
10,000+ science detectors	SPIDER (95/150/270)

Technologies	270 GHz arrays
In development:	40 GHz arrays
	dual-band 220/270s
	resonator bolometers

Berkeley Hardware Development

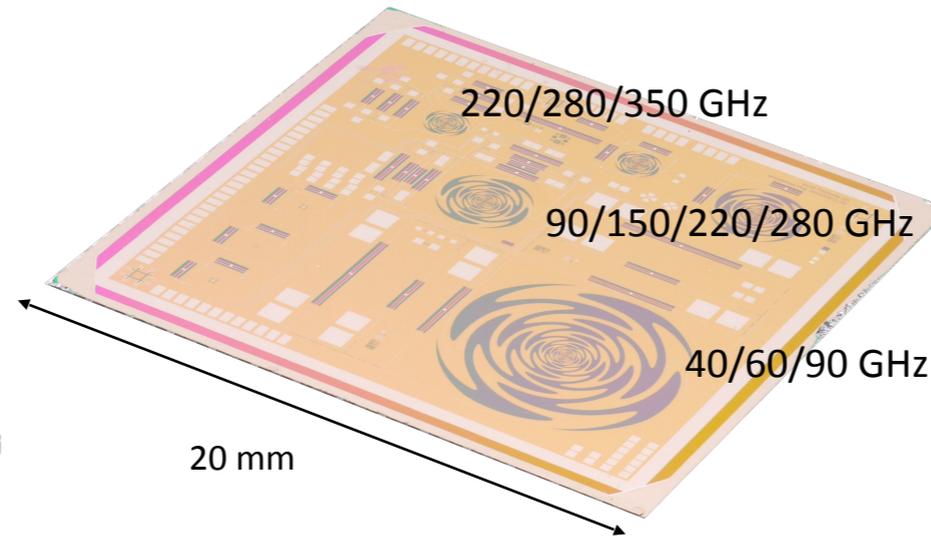


130 mm

Lenslet Coupled Antenna Multi-chroic Detector Module

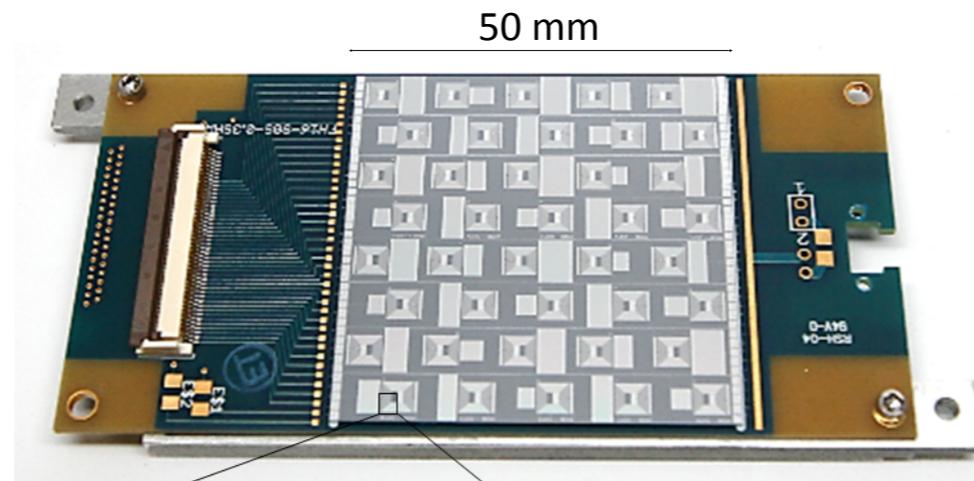
TRL: 4

Suzuki, LTD-16 (2015)



Sinuous Antenna Multi-chroic Pixel

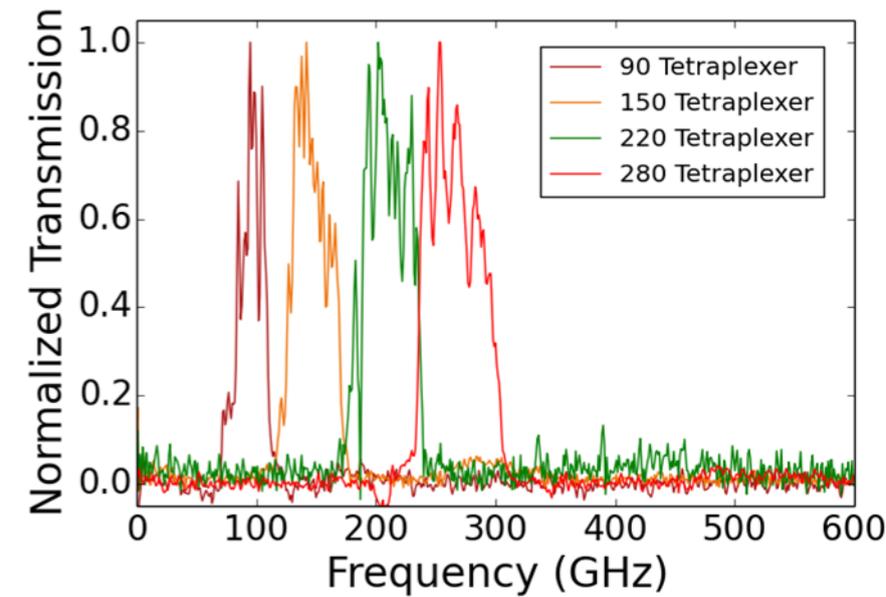
TRL: 4



Monolithic Lithographed Superconducting Resonators

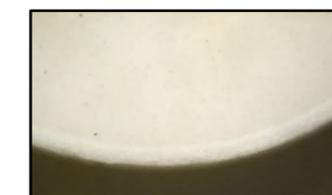
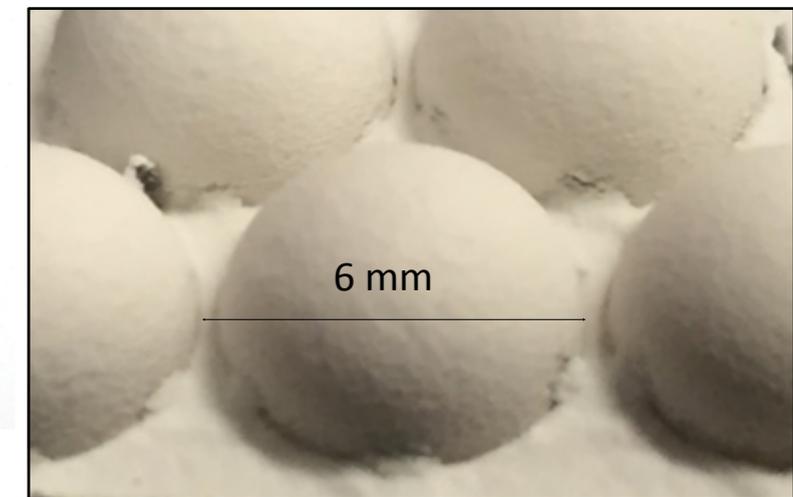
TRL: 4

Rotermund, LTD-16 (2015)



Tetraplexer Spectra

Westbrook, LTD-16 (2015)



Cross-section of thermal spray coated lenslets

Broadband Plasma Sprayed Anti-Reflection Coating

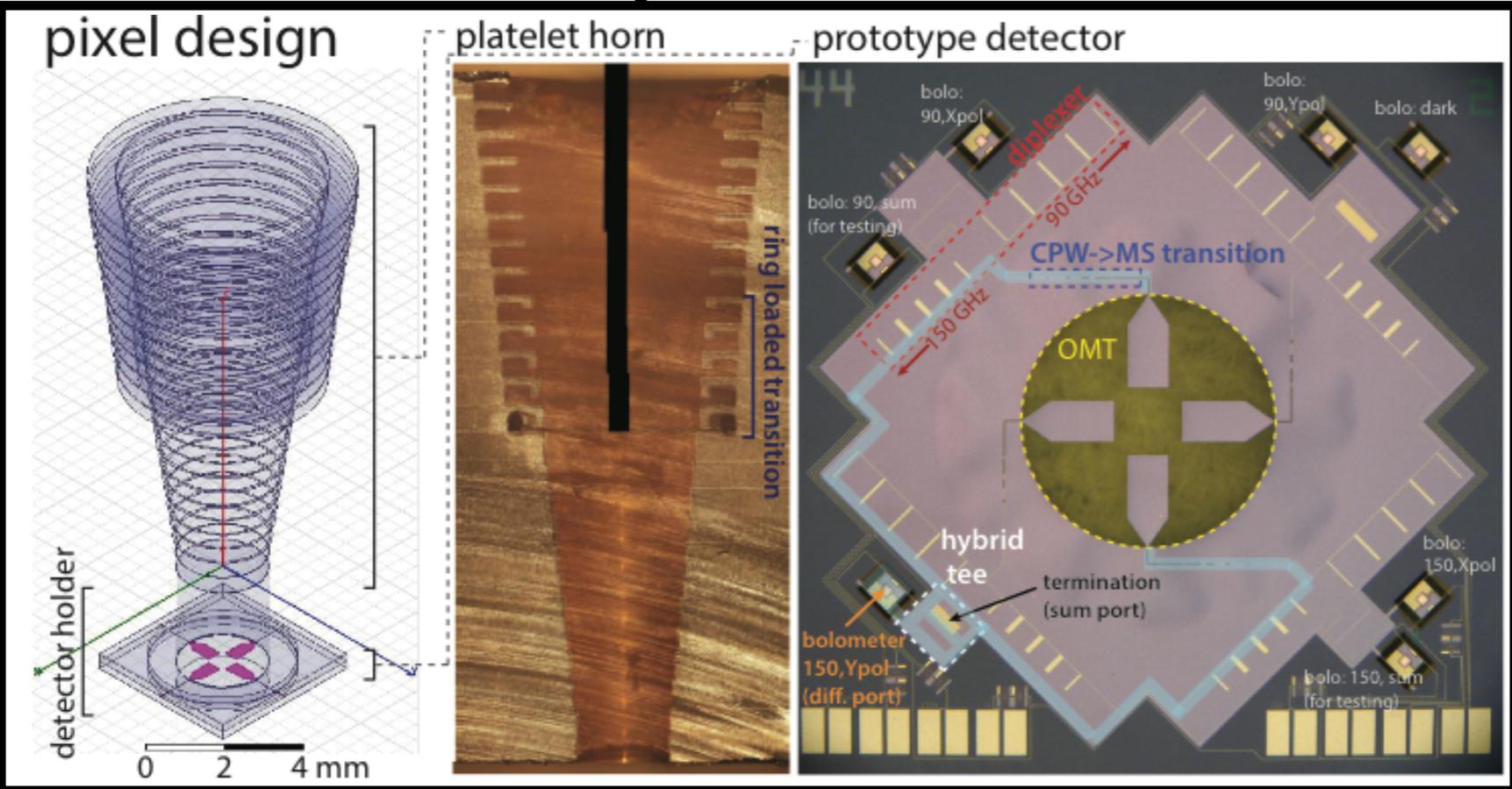
TRL: 4

Jeong, LTD-16 (2015)

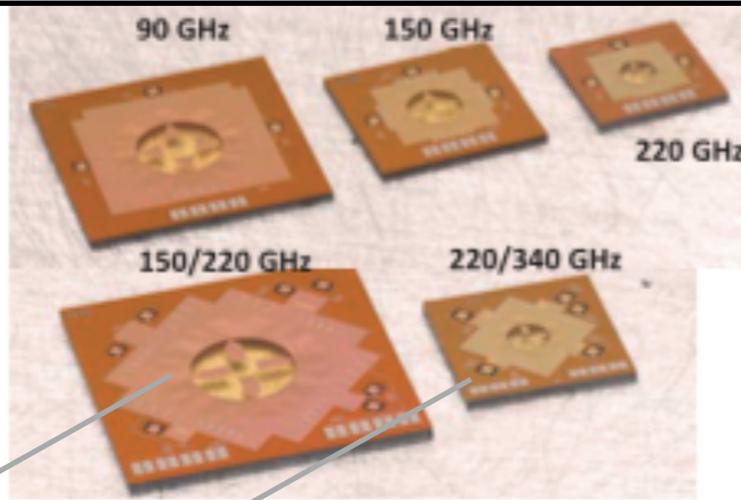
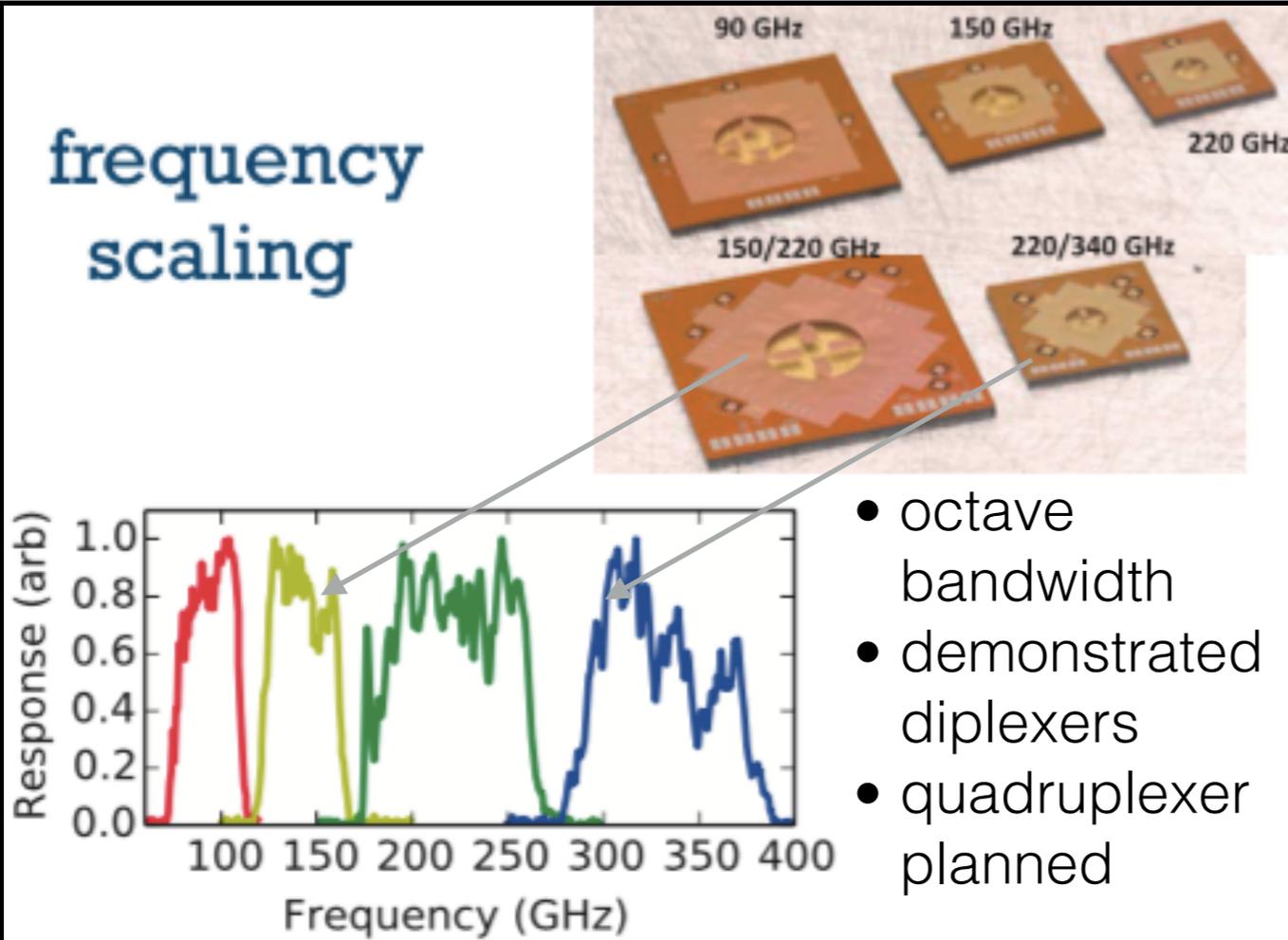
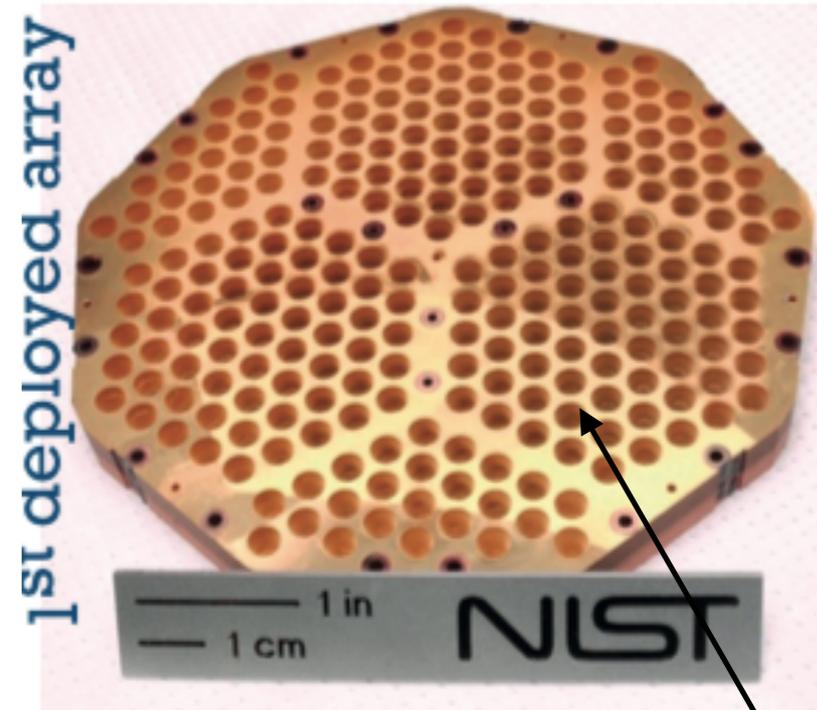


Marvell NanoLab

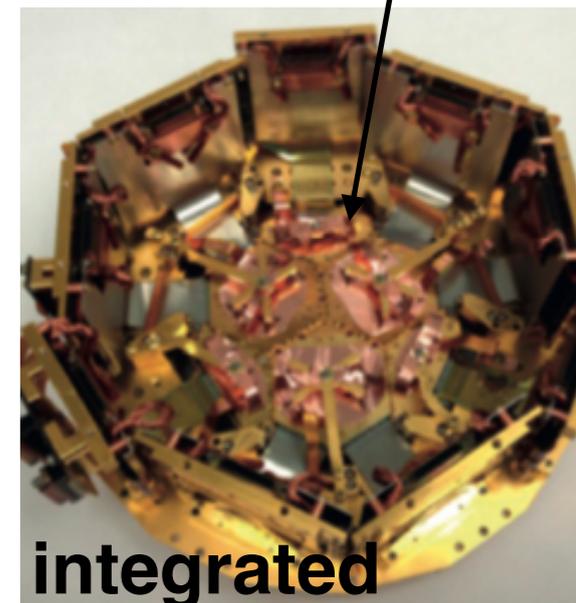
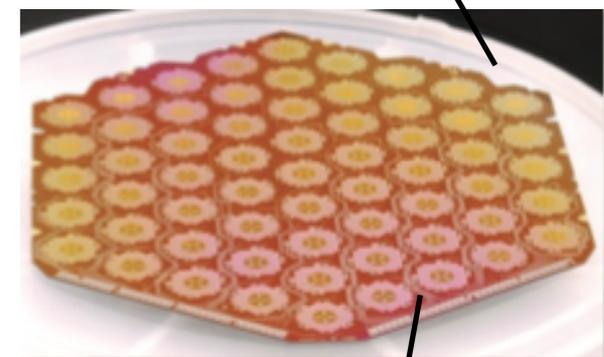
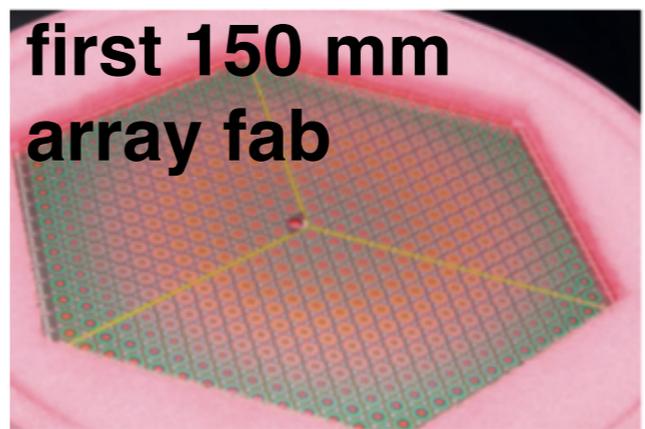
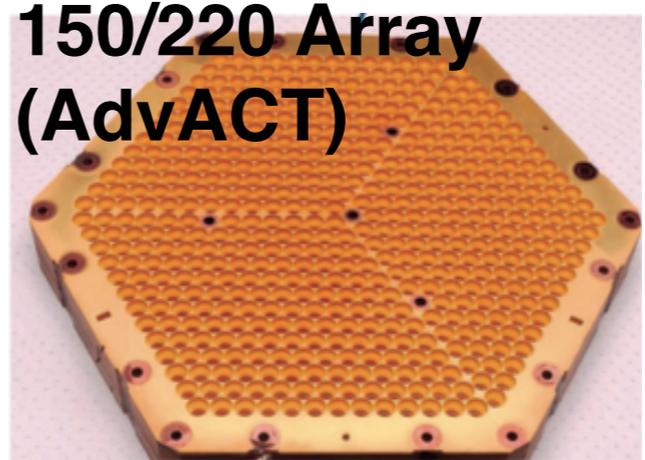
NIST: Horn Coupled Polarimeters



90/150 Multichroic Array

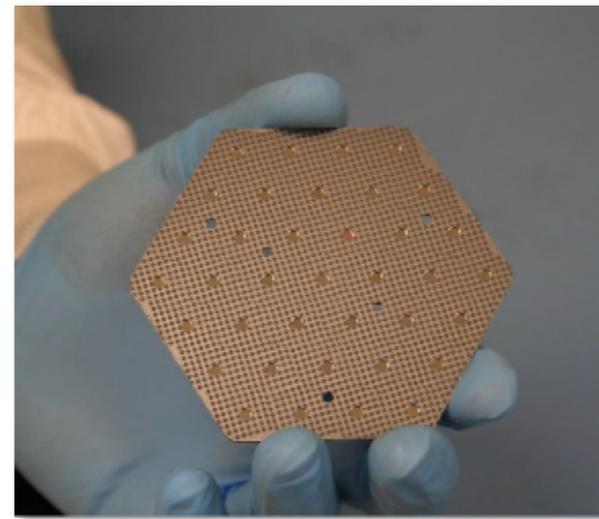
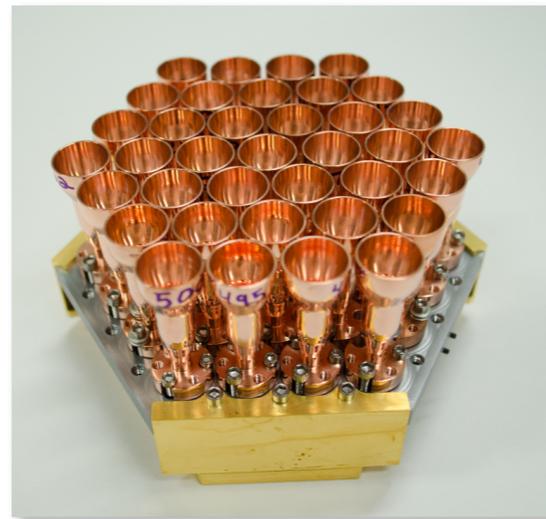
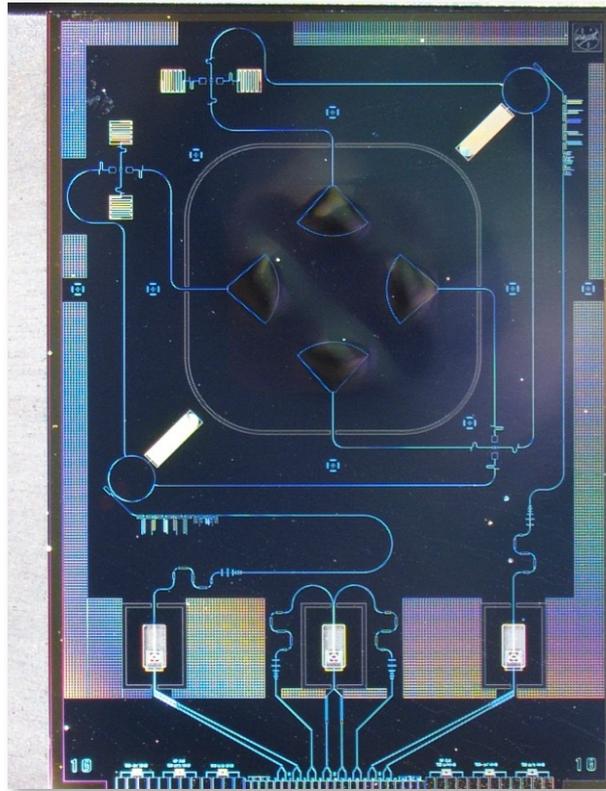


150/220 Array (AdvACT)

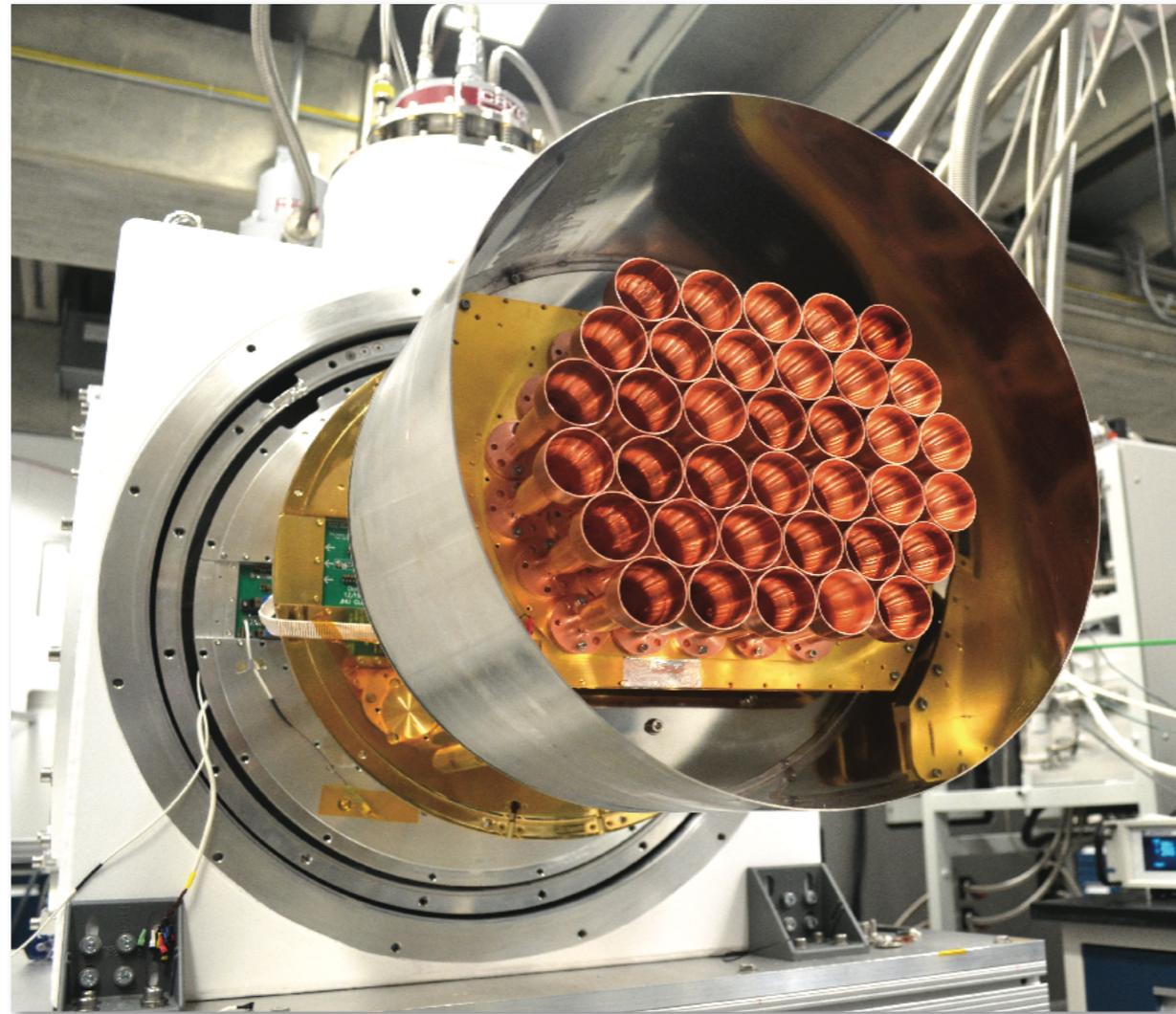
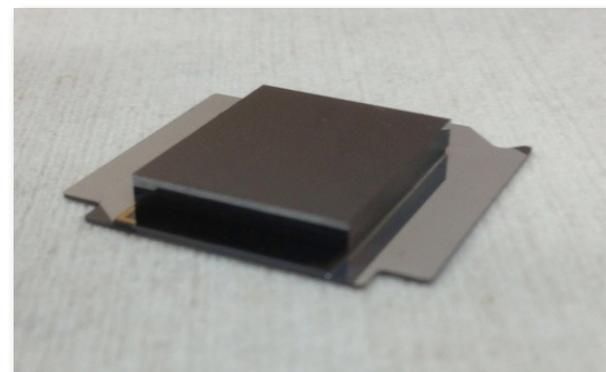
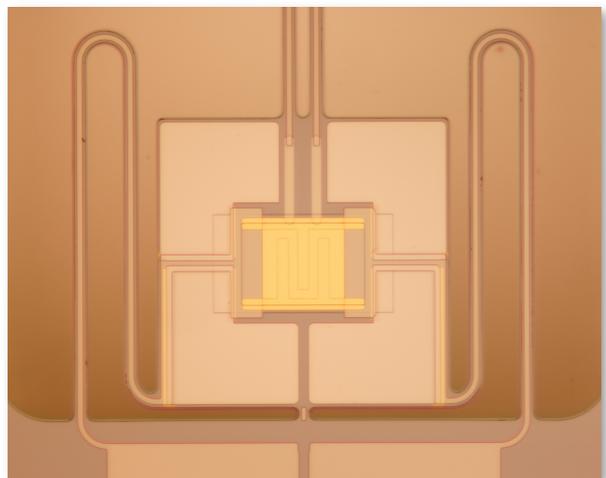
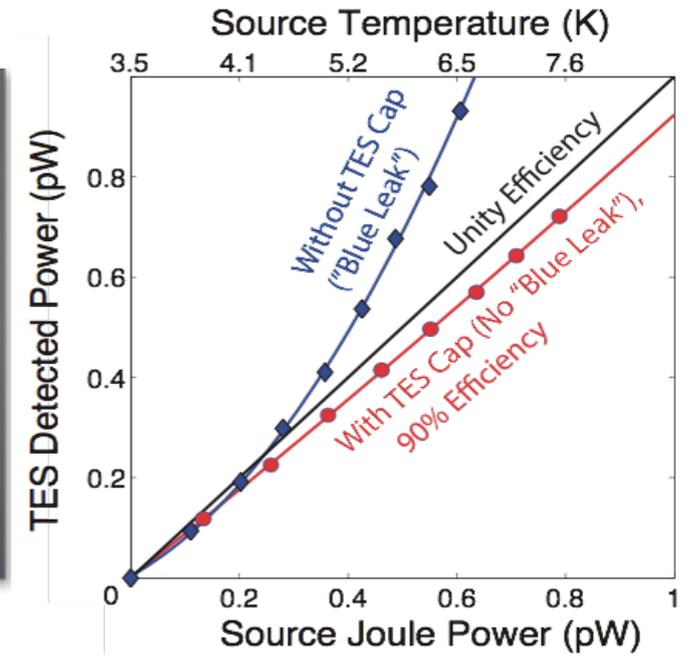


integrated with readout

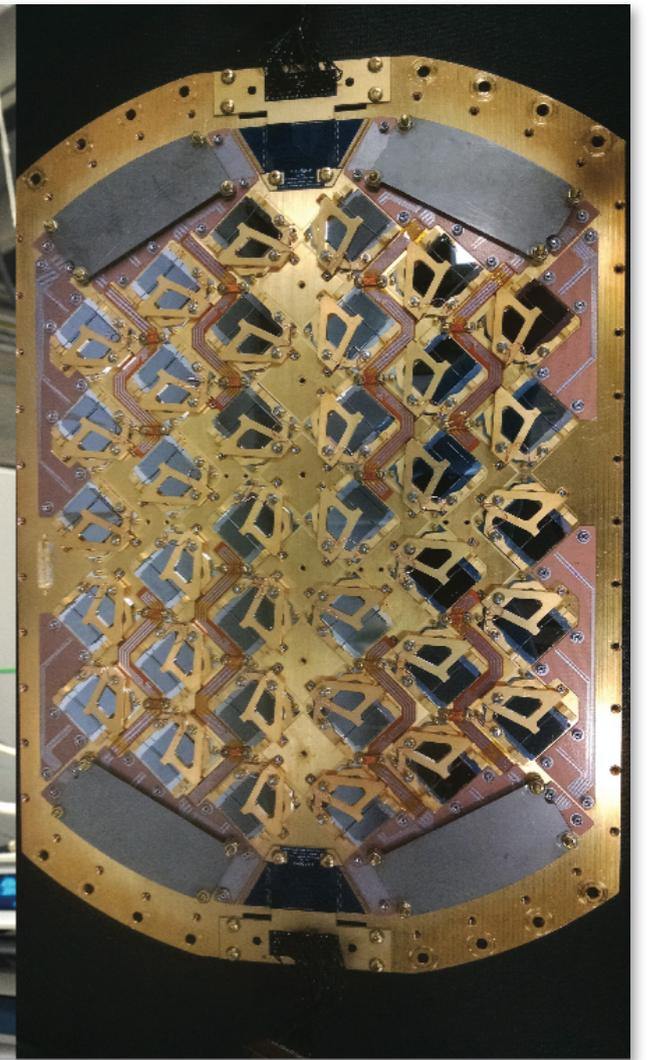
GSFC: Polarization-Sensitive Feed-Coupled TES



90 GHz CLASS Detector Module



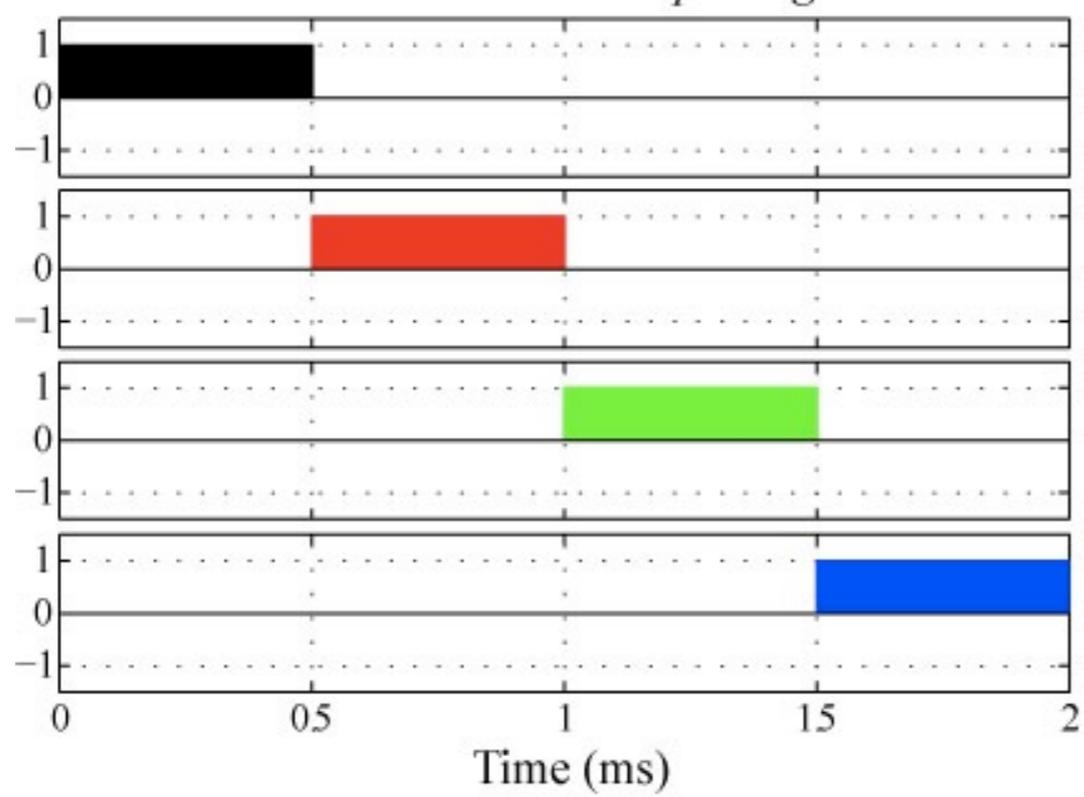
40 GHz CLASS Array Integration and Test (JHU)



Wollack (NASA/GSFC) et al.

Detector Readout

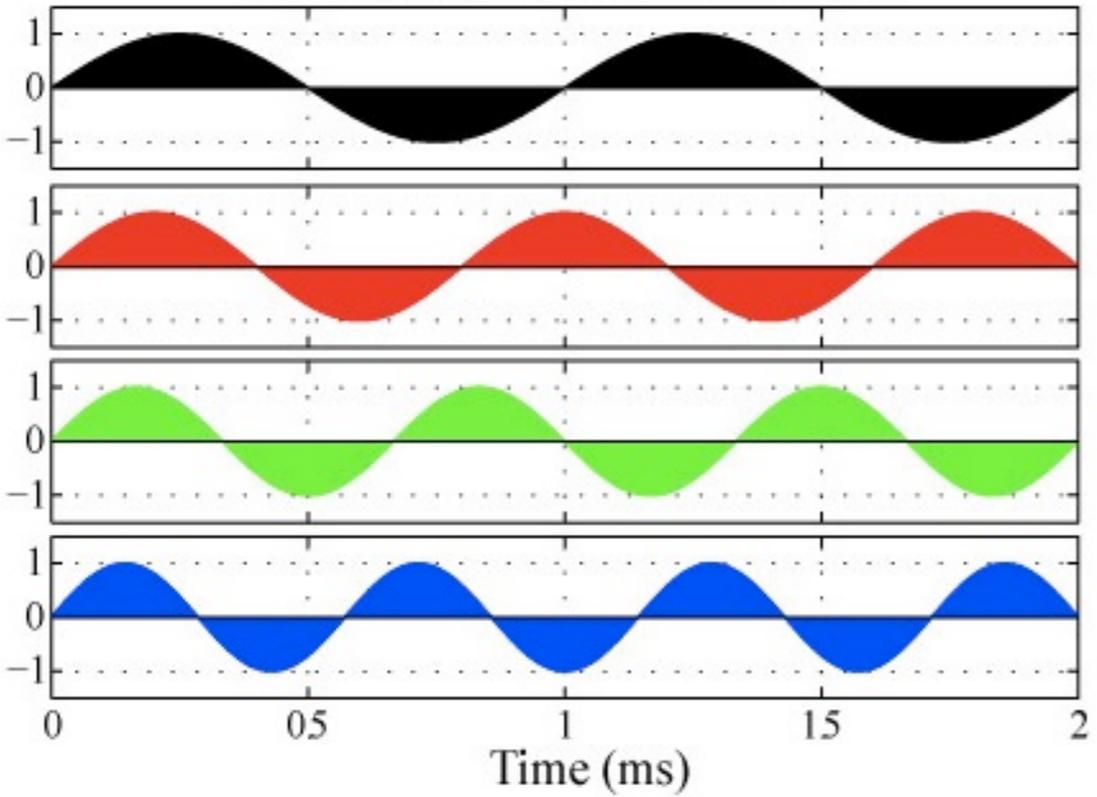
Time-division multiplexing



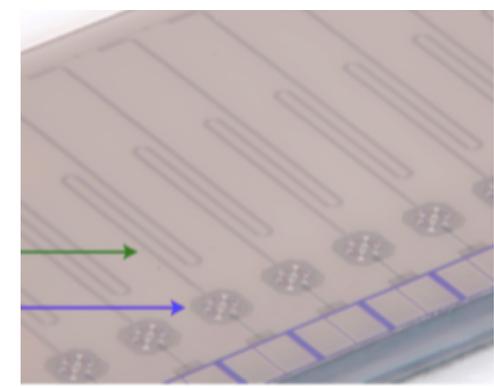
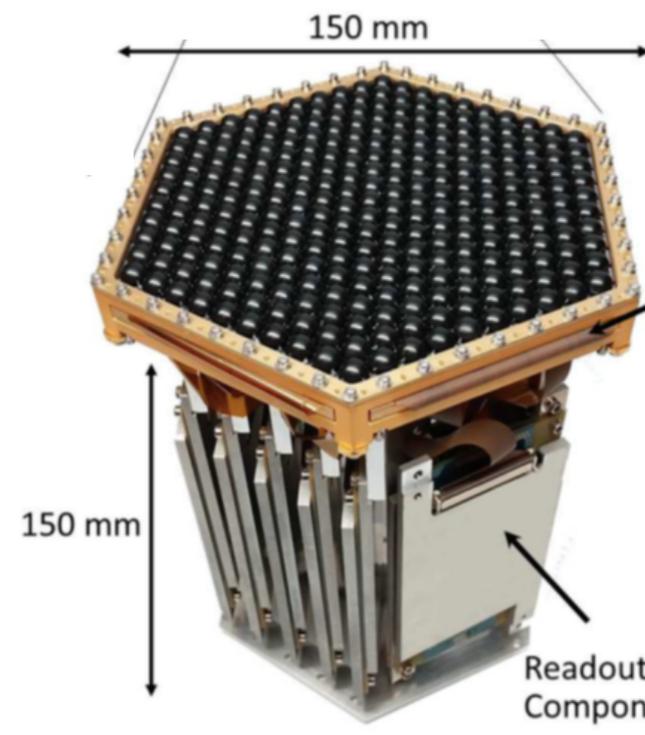
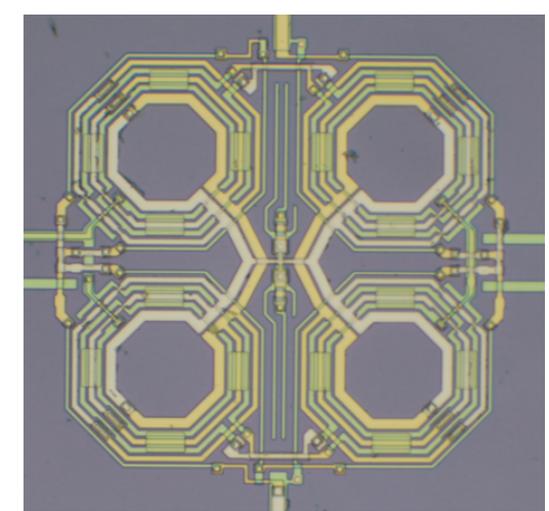
Time-division multiplexing
status: 64 channel /
SCUBA-2 arrays operating
with 10^4 TES

MHz frequency-domain multiplexing
status: 68 channel /
demonstrated to > 1000
pixels

Frequency-division multiplexing



GHz frequency-domain multiplexing for TES and KIDS
status: potentially
thousands of TES (KID)
detectors per module, less
mature



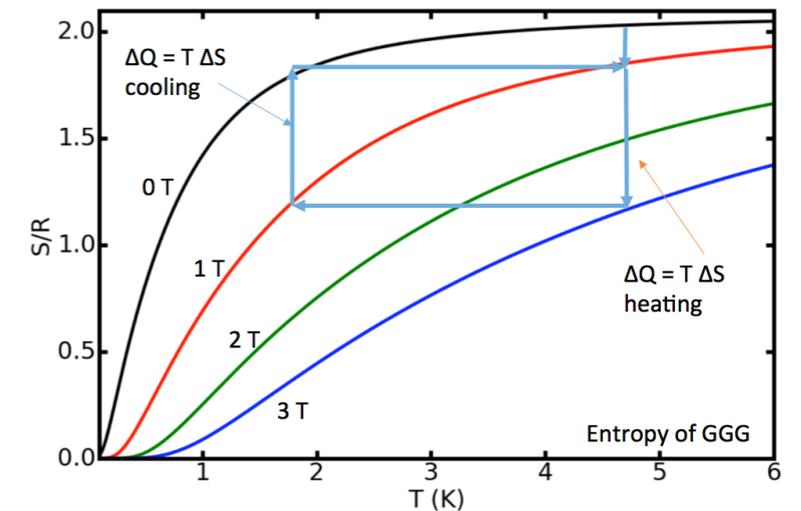
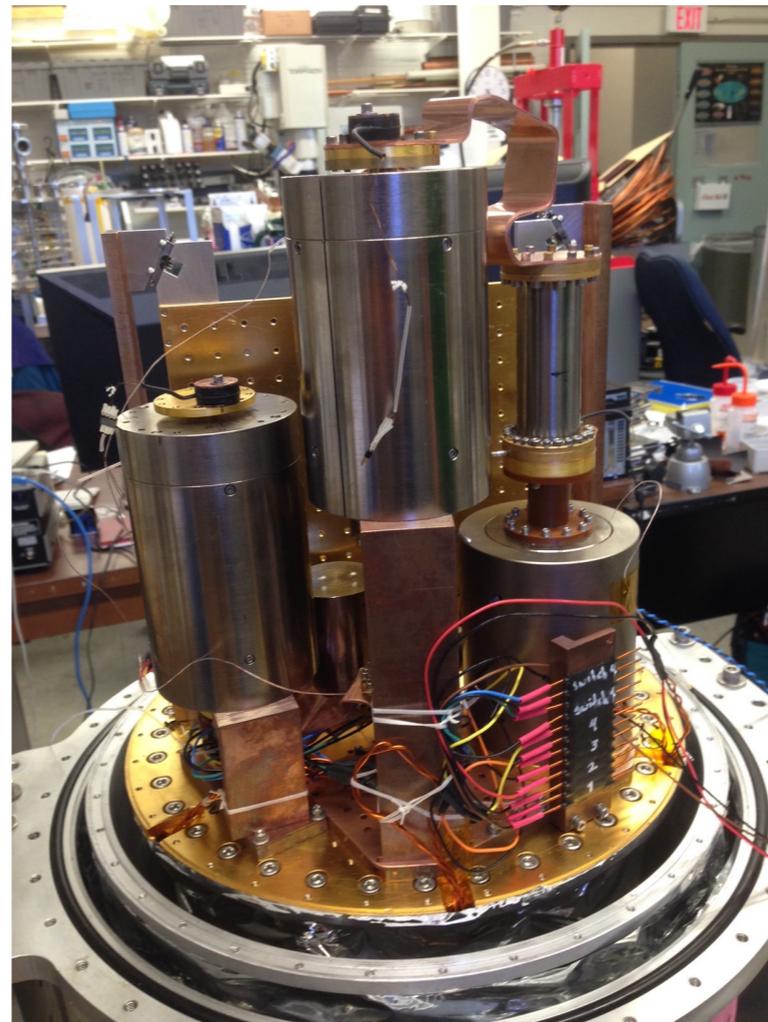
Cryogenics (100 mK cooling)

Planck Dilution Fridge



open cycle-> finite lifetime
TRL 9

GSFC Continuous ADR (Astro-H heritage)



Power = Energy per cycle / time per cycle
Premium: Fast cycle turn-around, high heat transfer rates, low gradients.



CPA pills with 30% thermal bus by volume, high G to salt.



Passive ³He HS; rapid switching, low parasitics.



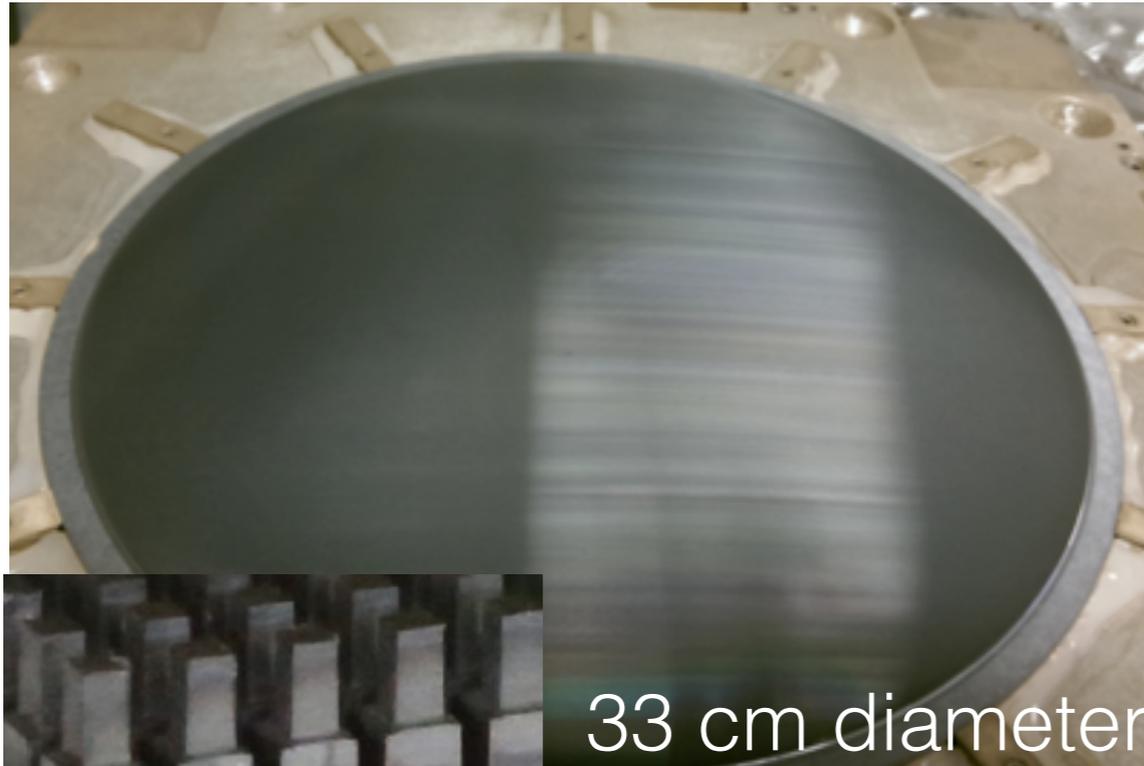
Superconducting heat switch (Pb) for 0.1 K operation.

4-10K cooling

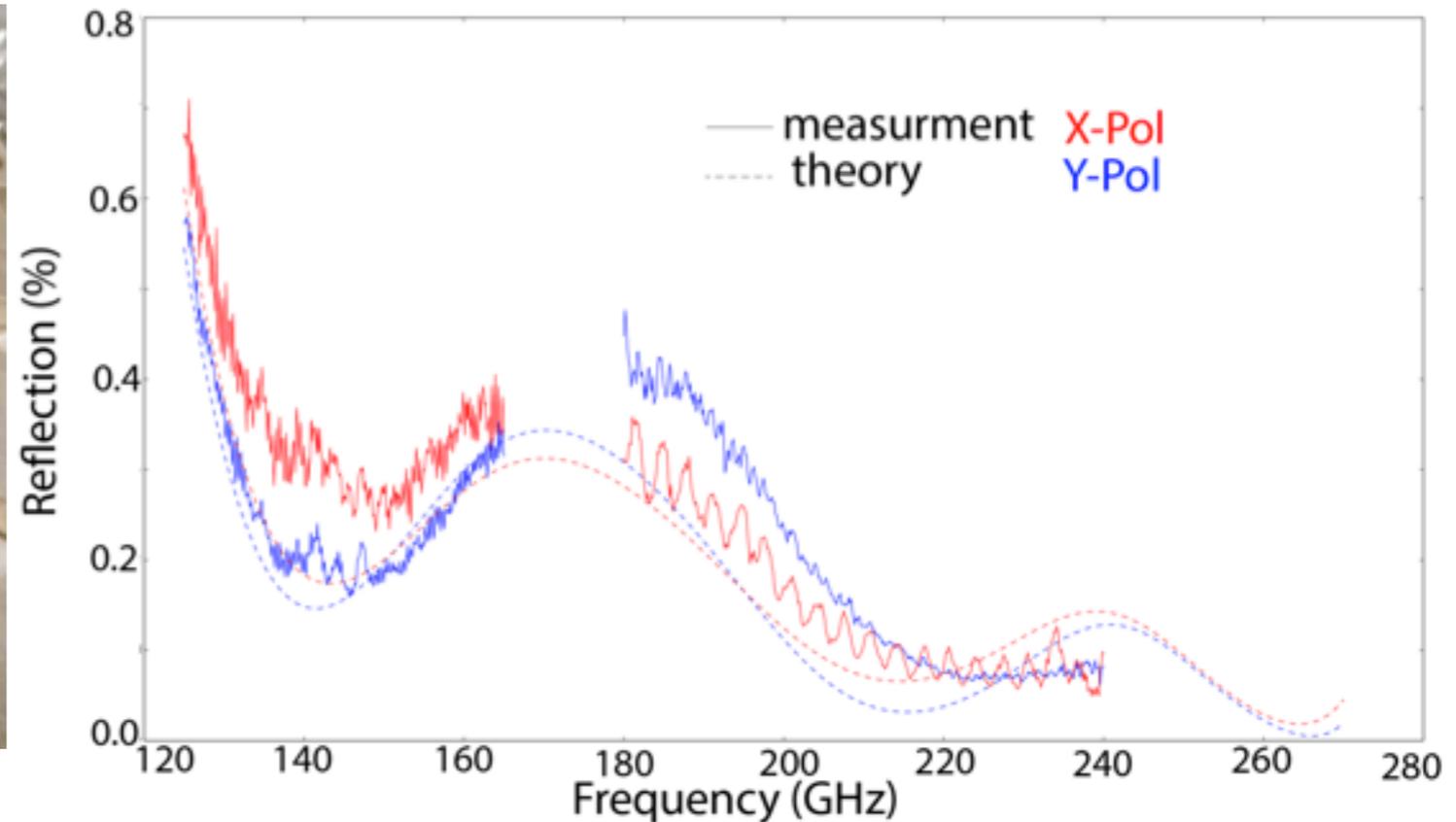
- MIRI cooler for JWST at high TRL for 4K cooling
- Astro-H flew with a JT cooler and an ADR
- Active area of development

Optical Elements: Lenses

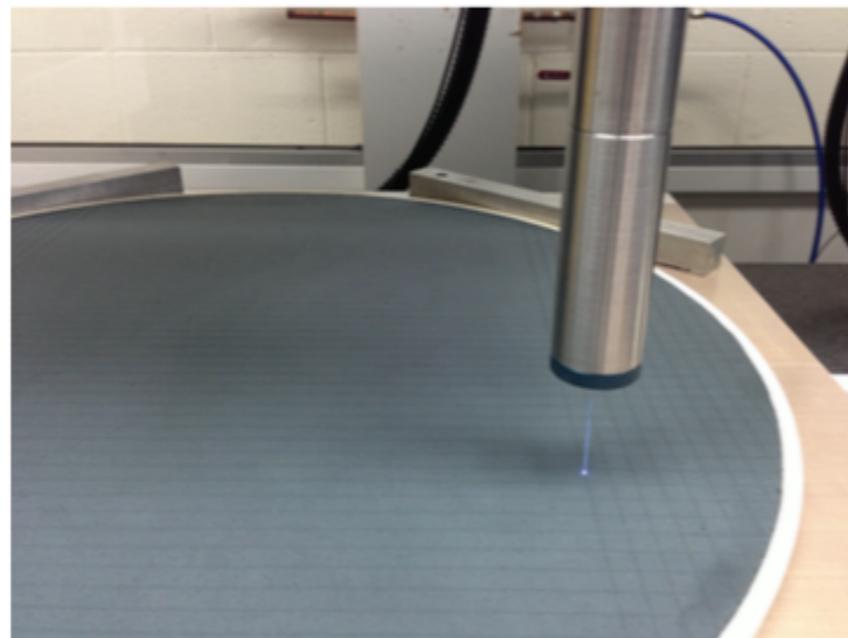
Metamaterial Anti-Reflection Coated Lenses (Michigan)



33 cm diameter



- sub wavelength features cut into silicon to approximate a multilayer coating (5 demonstrated)
- nine lenses deployed on ACTPol, will fly on PIPER



Epoxy Coatings (Stanford)

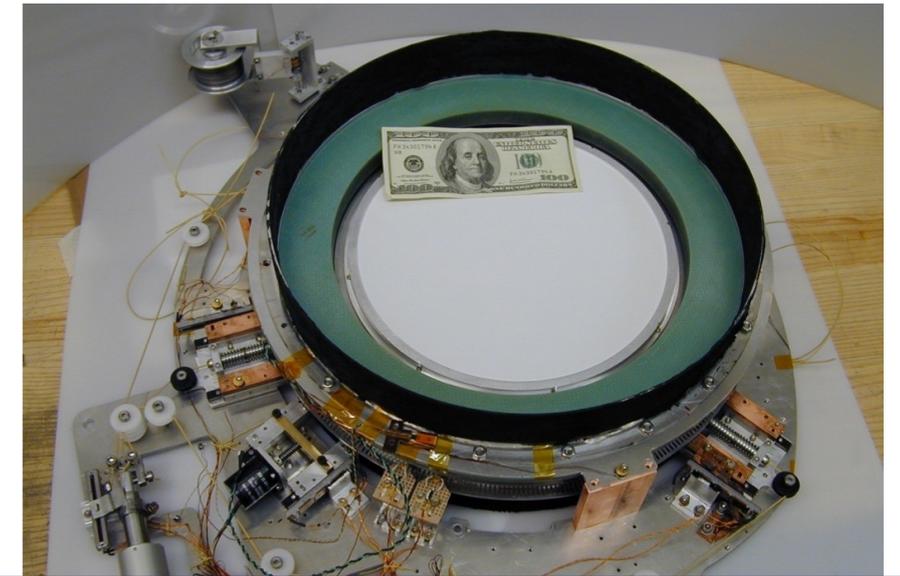
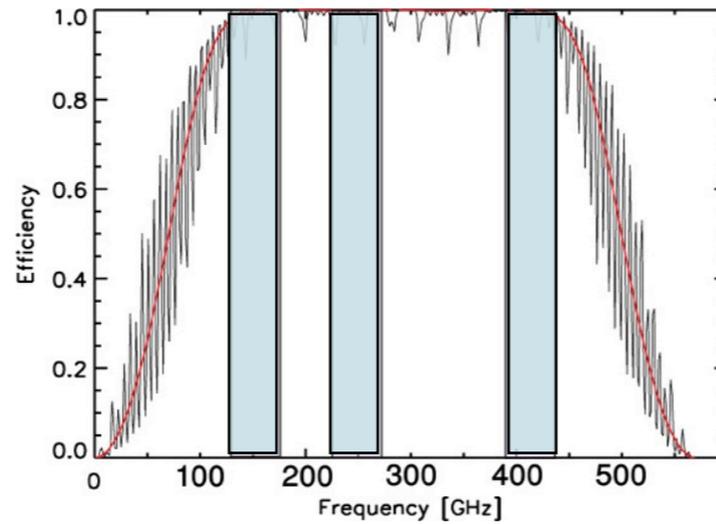
- epoxy cast and machined onto alumina lenses
- strain relieved by cutting a square grid pattern
- deployed on BICEP3
- being scaled to several layers

Optical Elements: Polarization Modulators

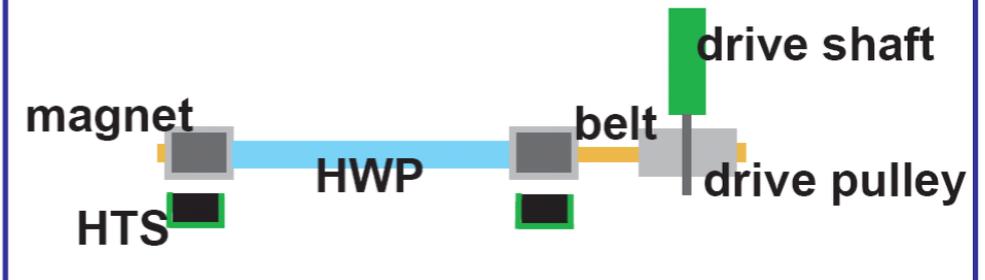
Broad-Band Half-Wave Plate (Minnesota)



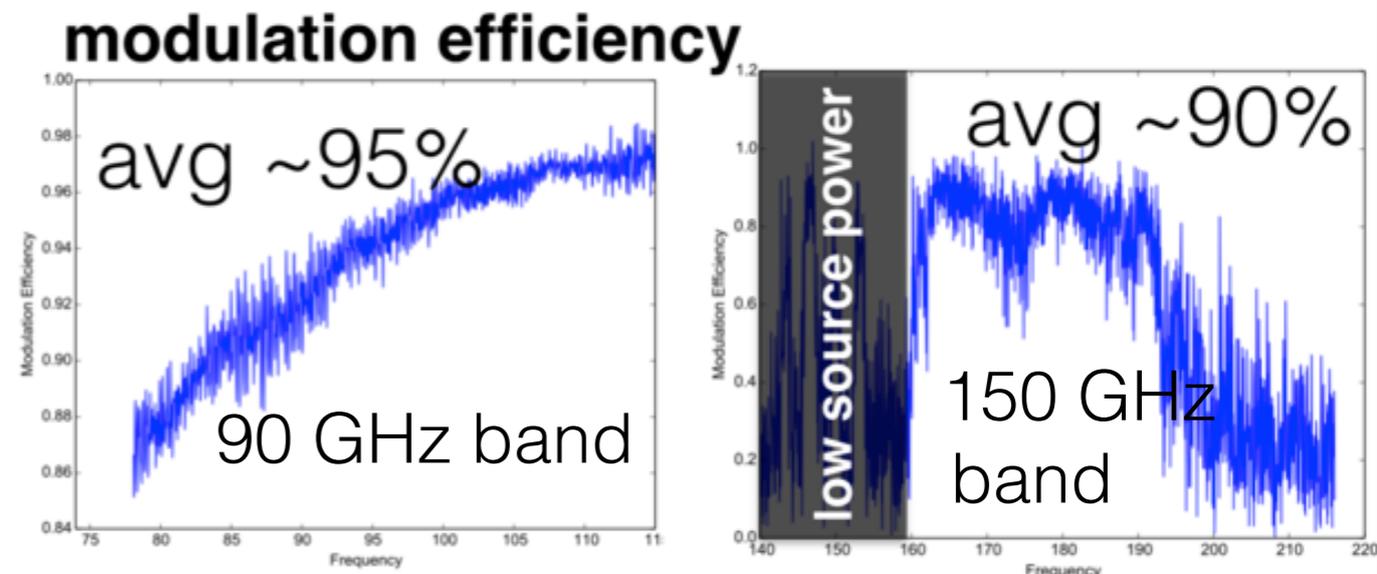
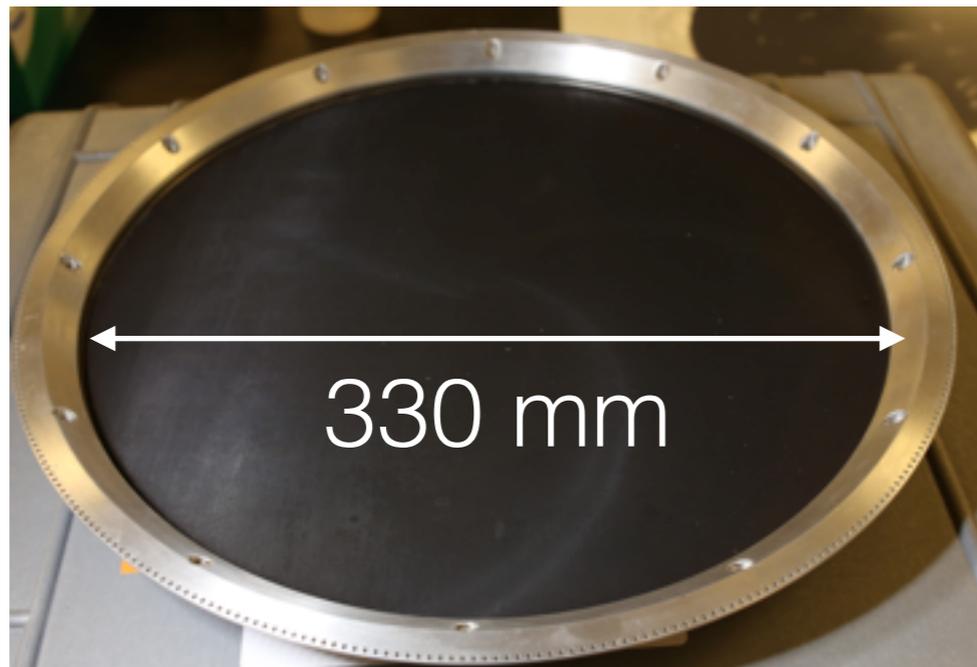
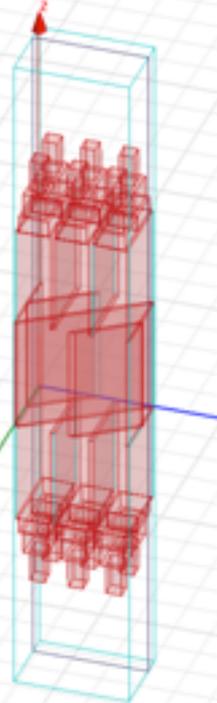
← 24 cm →



demonstrated a broadband HWP and continuous rotation with a high temperature superconducting bearing

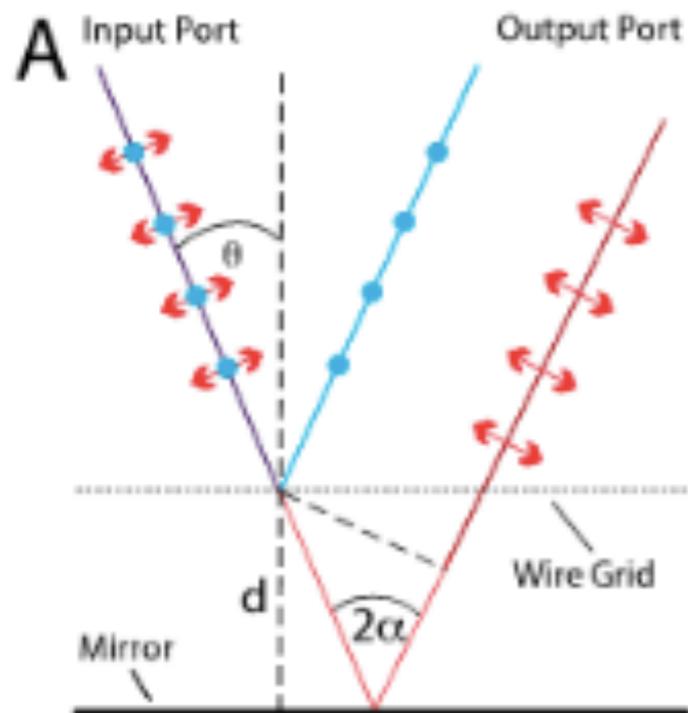


broad-band silicon metamaterial Half-Wave Plate (Michigan)



Optical Elements: Polarization Modulators

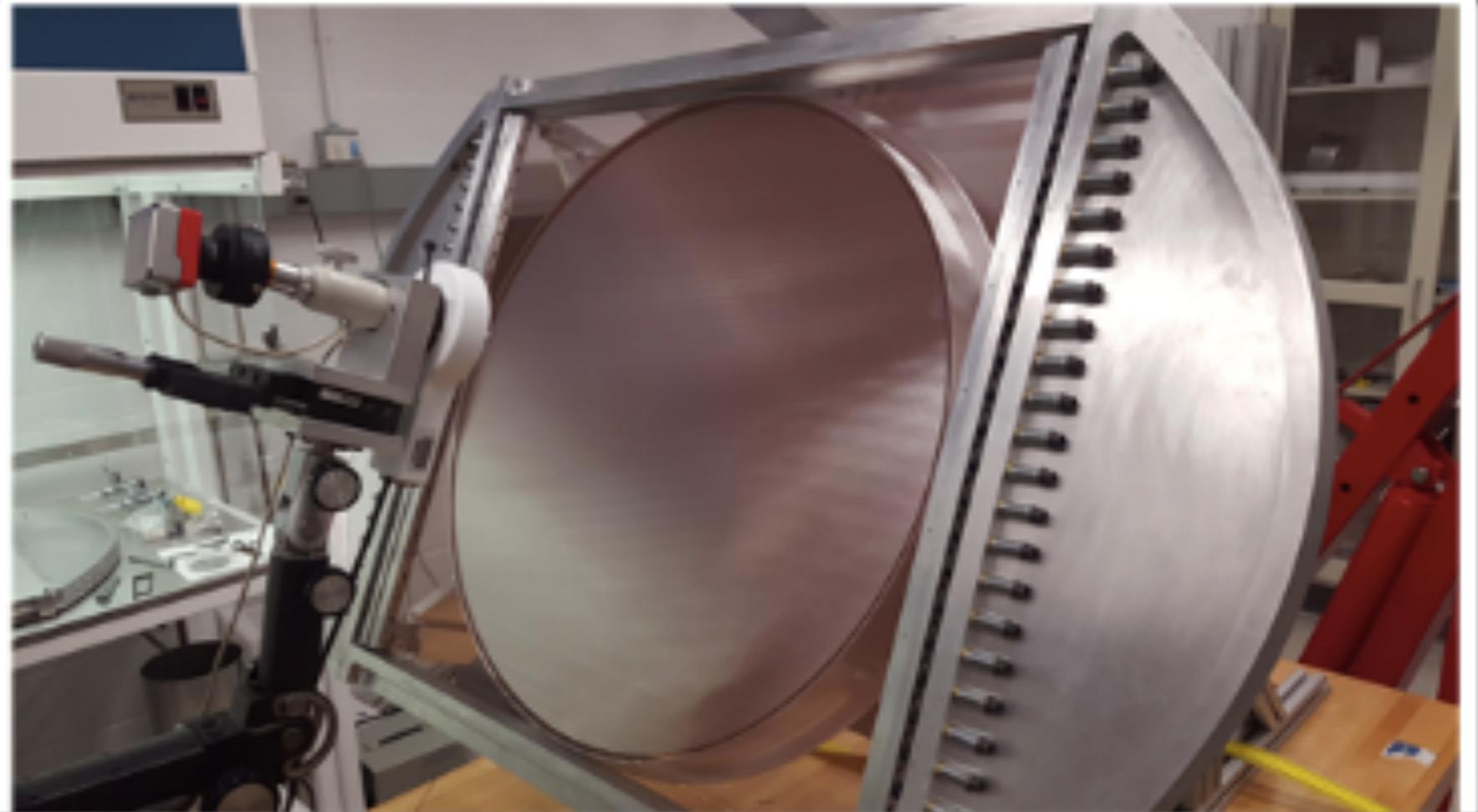
variable phase polarization modulator



- large diameter achievable
- last optical element before sky
- modulates between Q and V

CLASS

- Ground-based
- Atacama Desert, Chile
- Four frequencies: 40, 90, 150, 220 GHz
- Dual-frequency operation at 150/220 GHz
- 60 cm mirror, ambient-temperature
- Voice-coil drive, 10 Hz operation

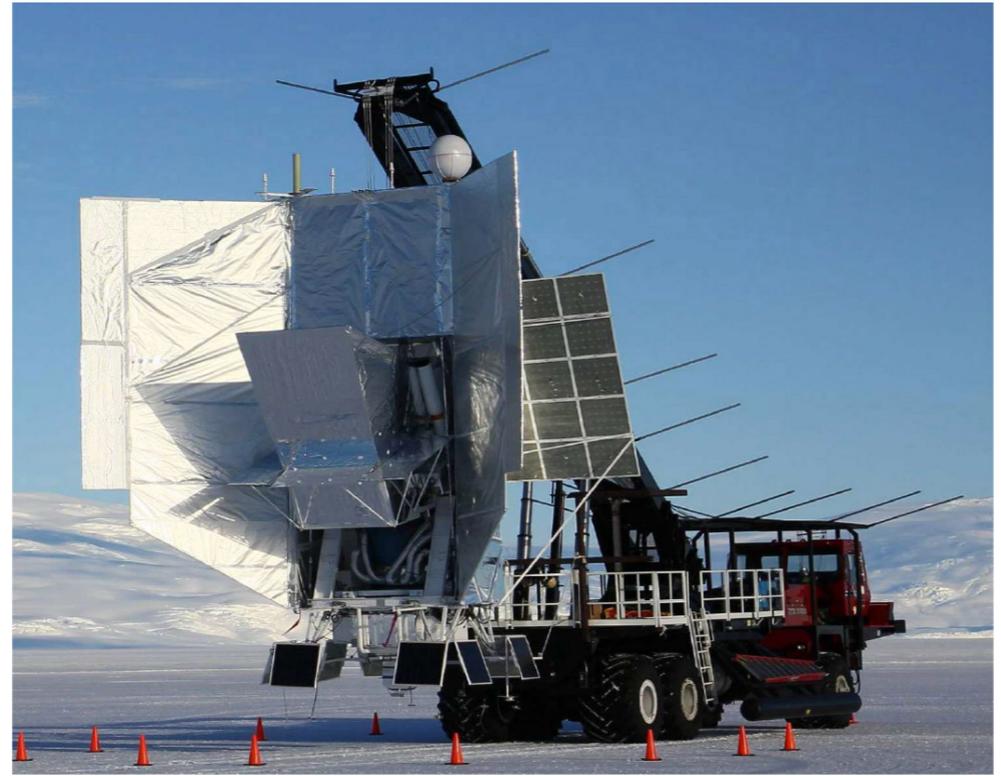


Sub-Orbital Demonstrations

SPIDER



EBEX

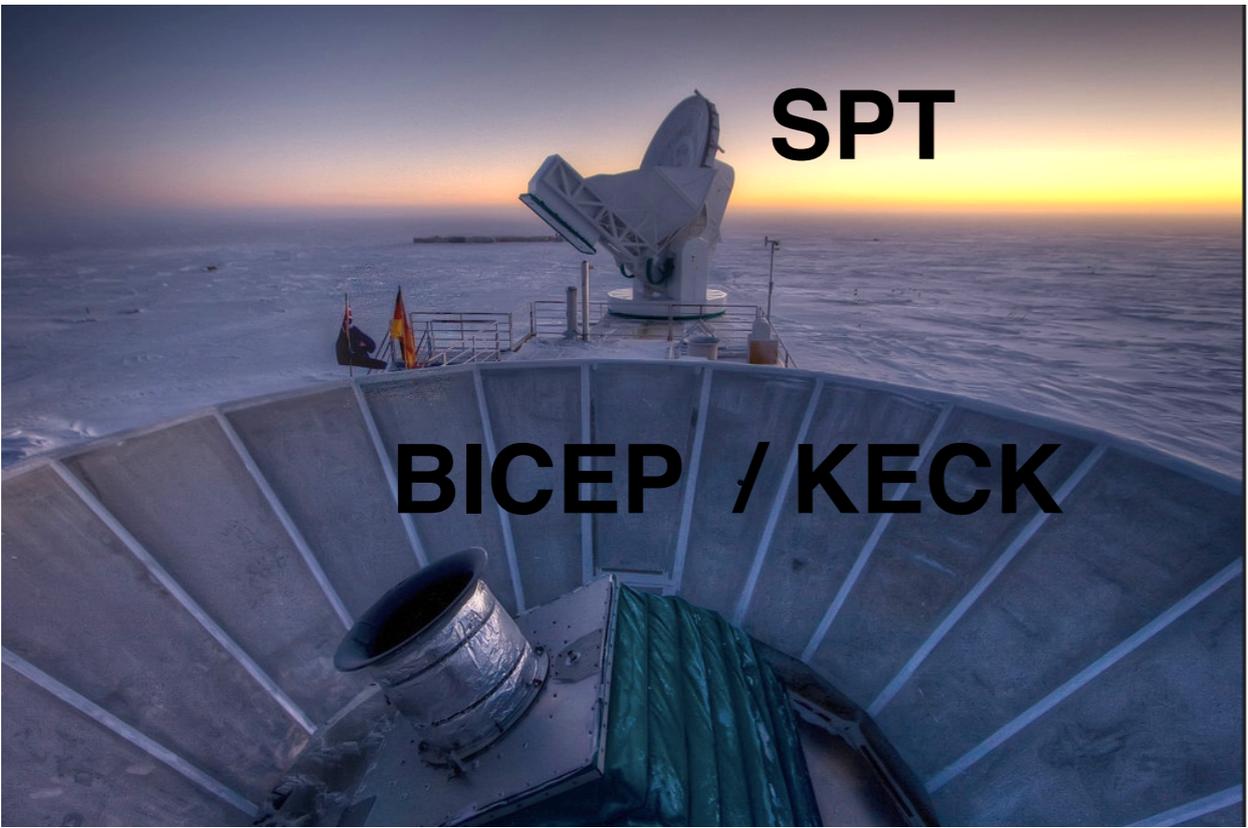


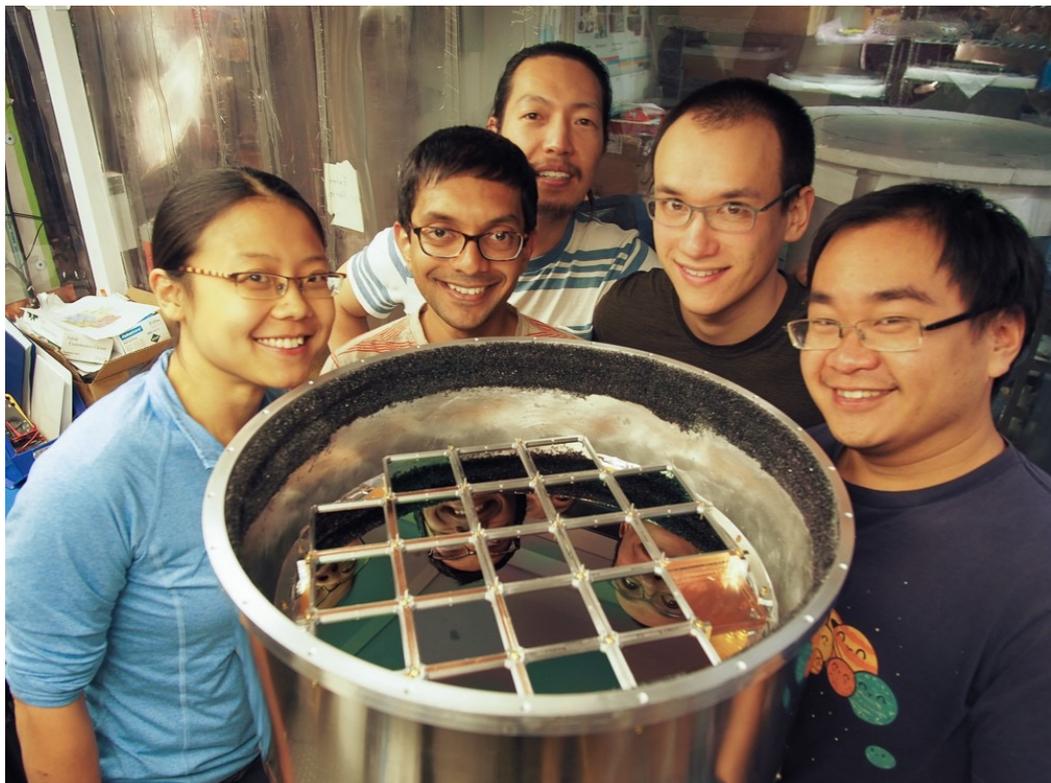
Flown On Balloons

- JPL and Berkeley detectors
- fMUX and tMUX
- HWP

Deployed on the Ground

- NIST, JPL, Berkeley detectors
 - metamaterial optics
- + much more coming soon**

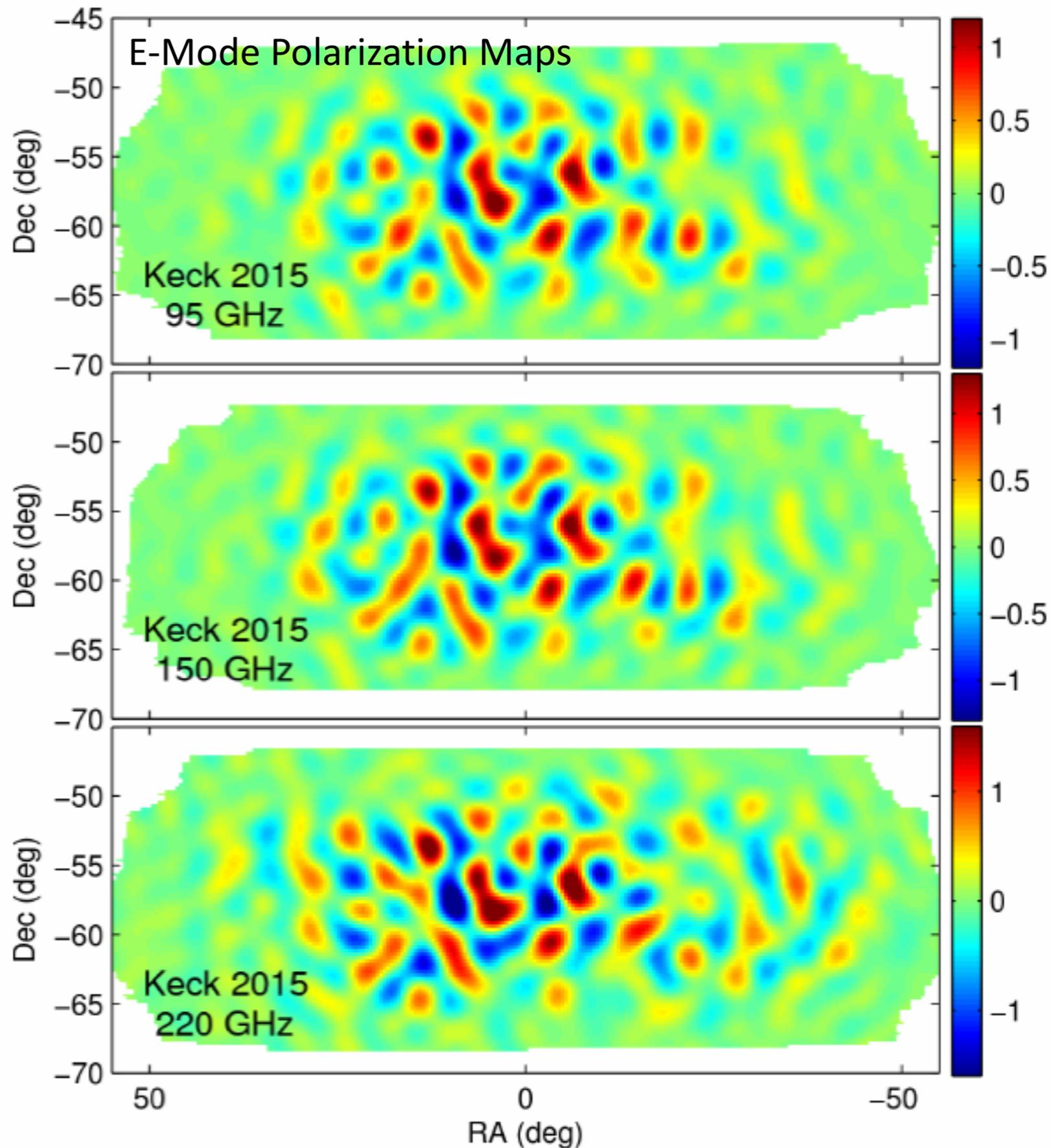




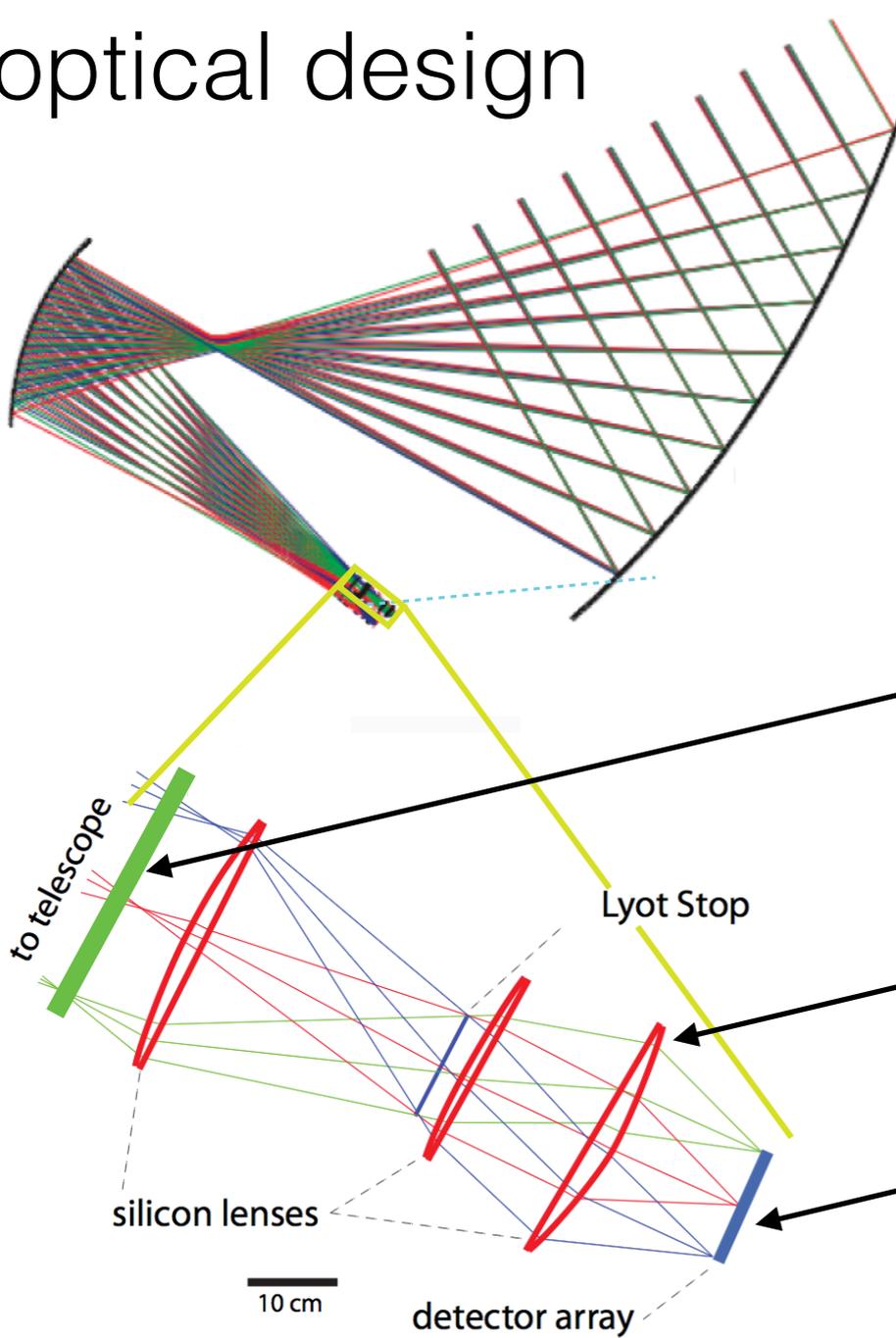
BICEP3 Operating Near Design Sensitivity
Modular focal plane technology scales to arbitrary size



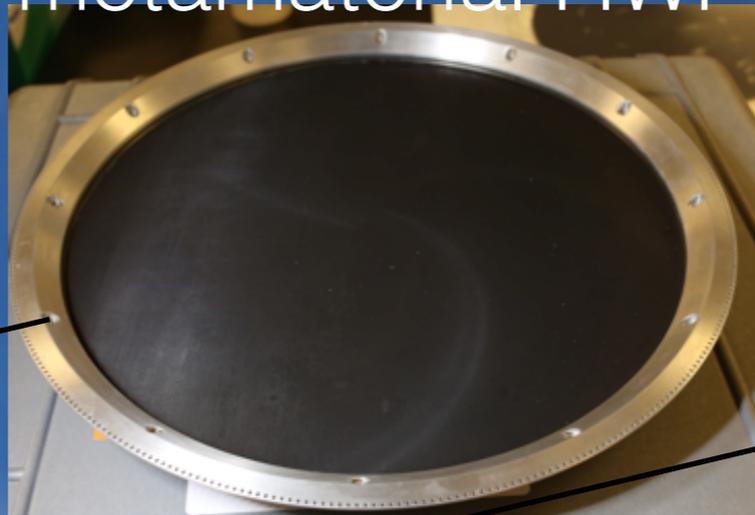
Keck Array Doubles 220 GHz Capability
Now 2048 detectors after successful 2015 demonstration



optical design



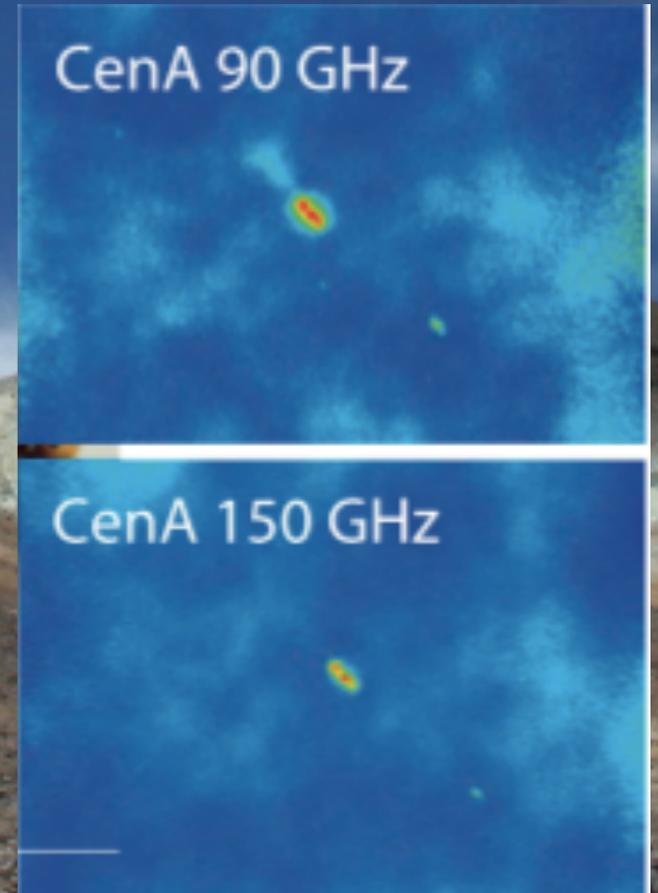
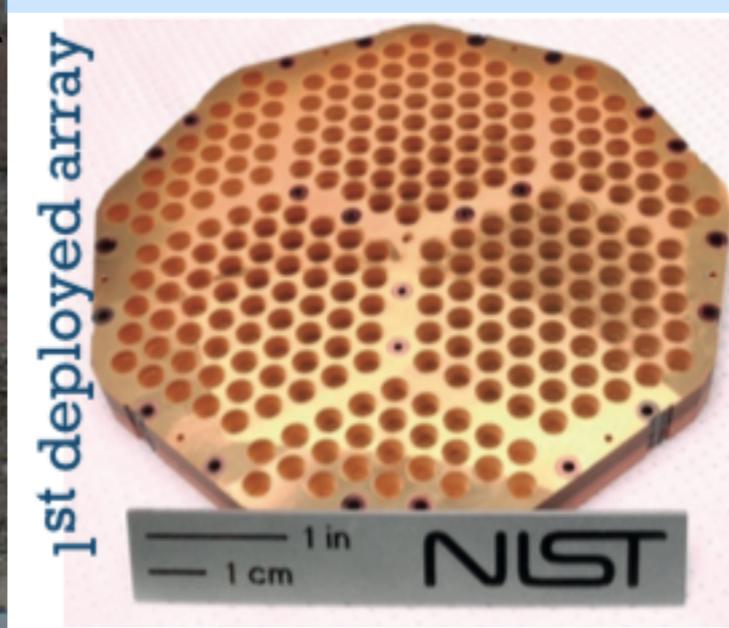
metamaterial HWP



metamaterial lens

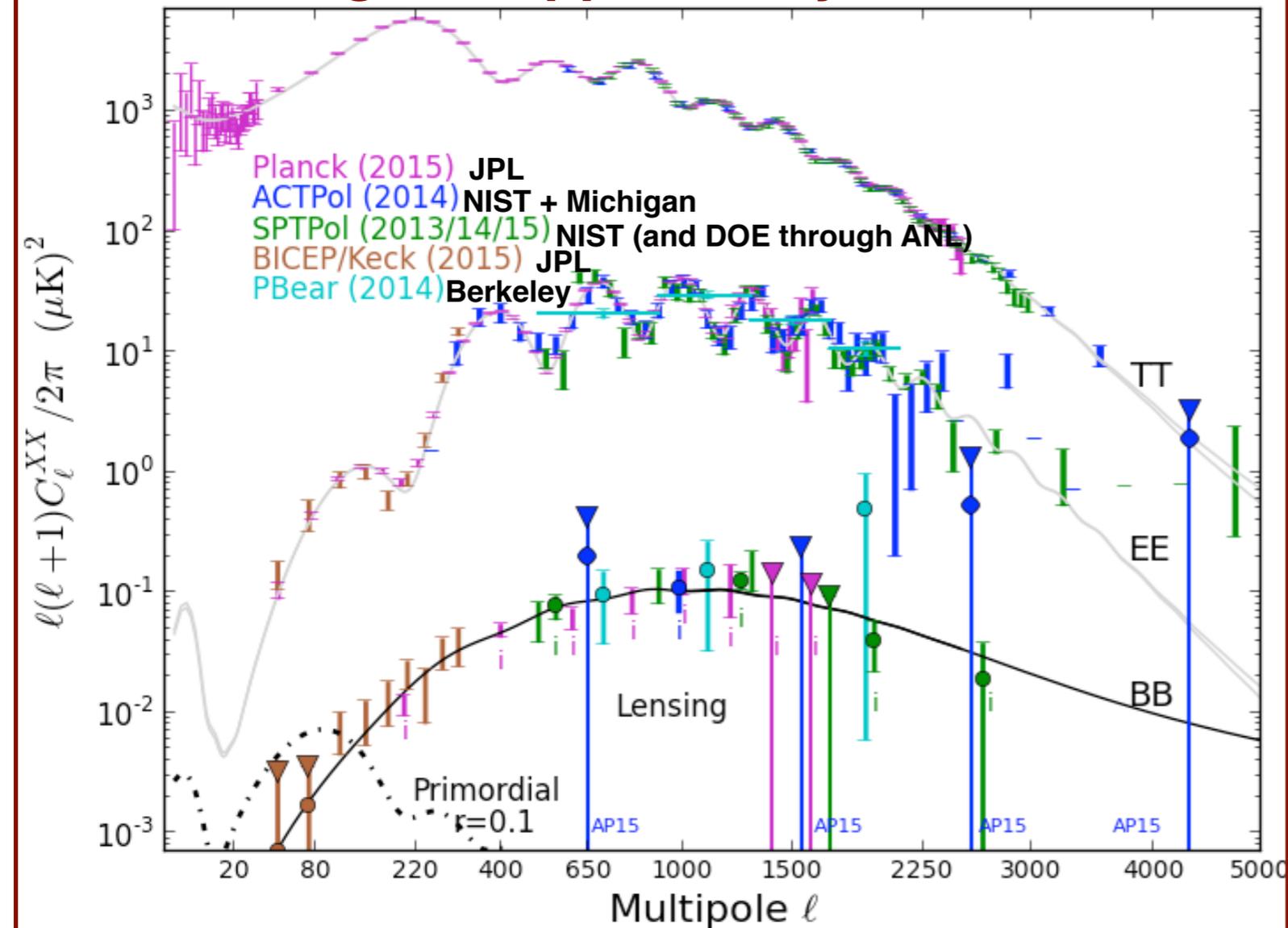


multichroic array



Conclusions

Scientific Impact of CMB technologies supported by NASA



NASA support for technology development has been crucial to advancing the state of the art in CMB measurement.

- Detectors, readout, optics, and cryogenics deployed and therefore at high TRL
- TRL must be assessed relative to the final application
 - 2015 PCOS PATR identified detectors, optical elements, and cryogenics as gaps
- CMB Technology development is dynamic with many advances on the horizon